U–Pb zircon ages, mapping, and biostratigraphy of the Payette Formation and Idaho Group north of the western Snake River Plain, Idaho: Implications for hydrocarbon system correlation

Renee L. Love[1*], Reed S. Lewis[2], Spencer H. Wood[3], Dennis M. Feeney[2], and Mark D. Schmitz[3]

[1]Department of Earth and Spatial Sciences, University of Idaho, 875 Perimeter Dr. MS 3022, Moscow, ID 83844-3022

[2]Idaho Geological Survey, University of Idaho, 875 Perimeter Dr. MS 3014, Moscow, ID 83844-3014

[3]Department of Geosciences, Boise State University, 1910 University Dr. MS 1535, Boise, ID 83725-1535

**Correspondence should be addressed to: rlove@uidaho.edu*

ABSTRACT

Sedimentary deposits north of the western Snake River Plain host Idaho's first and only producing oil and gas field. They consist of the lower to middle Miocene Payette Formation, the middle to upper Miocene Poison Creek and Chalk Hills Formations, and the Pliocene to lower Pleistocene Glenns Ferry Formation. Using new geochronology, palynomorph biostratigraphy, and geologic mapping, we connect updip surface features to subsurface petroleum play elements. The Payette Formation is a likely main source of the hydrocarbons, and acts as one of the reservoirs in the unnamed basin. Here, we redefine the Payette Formation as 0 to ~3,500 ft (0 to ~1,000 m) of mudstone, with lesser amounts of sandstone overlying and interbedded with the Columbia River Basalt Group and Weiser volcanic field. Index palynomorphs, including *Liquidambar* and *Pterocarya*, present in Idaho during and immediately after the middle Miocene climatic optimum, and new U–Pb ages of 16.39 and 15.88 Ma, help establish the thickness and extent of the formation. For the first time, these biostratigraphic markers have been defined for the oil and gas wells. The Poison Creek Formation is sandstone interbedded with mudstone that is ~800–1,800 ft (250–550 m) thick. The Chalk Hills Formation is a tuffaceous siltstone, claystone, and sandstone that is as much as ~4,200 ft (1,280 m) thick. New U–Pb ages are 10.1, 9.04, and 9.00 for the Poison Creek Formation, along with maximum depositional ages of 10.7 to 9.9 Ma for four samples from the Poison Creek Formation. A single U–Pb age of 7.78 Ma was determined from pumice low in the Chalk Hills Formation. Like the Payette Formation, the Poison Creek Formation can be a reservoir, whereas the Chalk Hills Formation acts as a sealing mudstone facies. The overlying sandstone, siltstone, and conglomerate of the Glenns Ferry Formation act as the overburden to the petroleum system in the subsurface, and were important for burial and hydrocarbon maturation. The Glenns Ferry Formation is up to 500 ft (150 m) thick in the study area, as much has been eroded. Whereas the Payette and Poison Creek Formations were deposited during the mid-Miocene climatic optimum amongst and above volcanic flows, the Chalk Hills and Glenns Ferry Formations were deposited within ancient Lake Idaho during an overall increase in aridity and cooling after the mid-Miocene climatic optimum.

KEY WORDS: biostratigraphy, hydrocarbon, Idaho, Idaho Group, Lake Idaho, mapping, mid-Miocene climatic optimum, palynology, Payette Formation.

INTRODUCTION

Miocene and younger sedimentary deposits are exposed within and on the flanks of the western Snake River Plain (WSRP; Figs. 1 and 2). Fluvial and lacustrine depositional systems existed in southwest Idaho and adjacent southeast Oregon from the early Miocene to early Pleistocene. The resulting sedimentary rocks have been named the 'Payette Formation' of the early–middle Miocene (Eldridge, 1896; Lindgren, 1898; Kirkham, 1930) and the Idaho Group, the latter of which includes the middle–late Miocene Poison Creek and Chalk Hills

Received 3 January 2022 • Revised submitted 26 March 2023 • Accepted 5 April 2023 • Published online November 2023

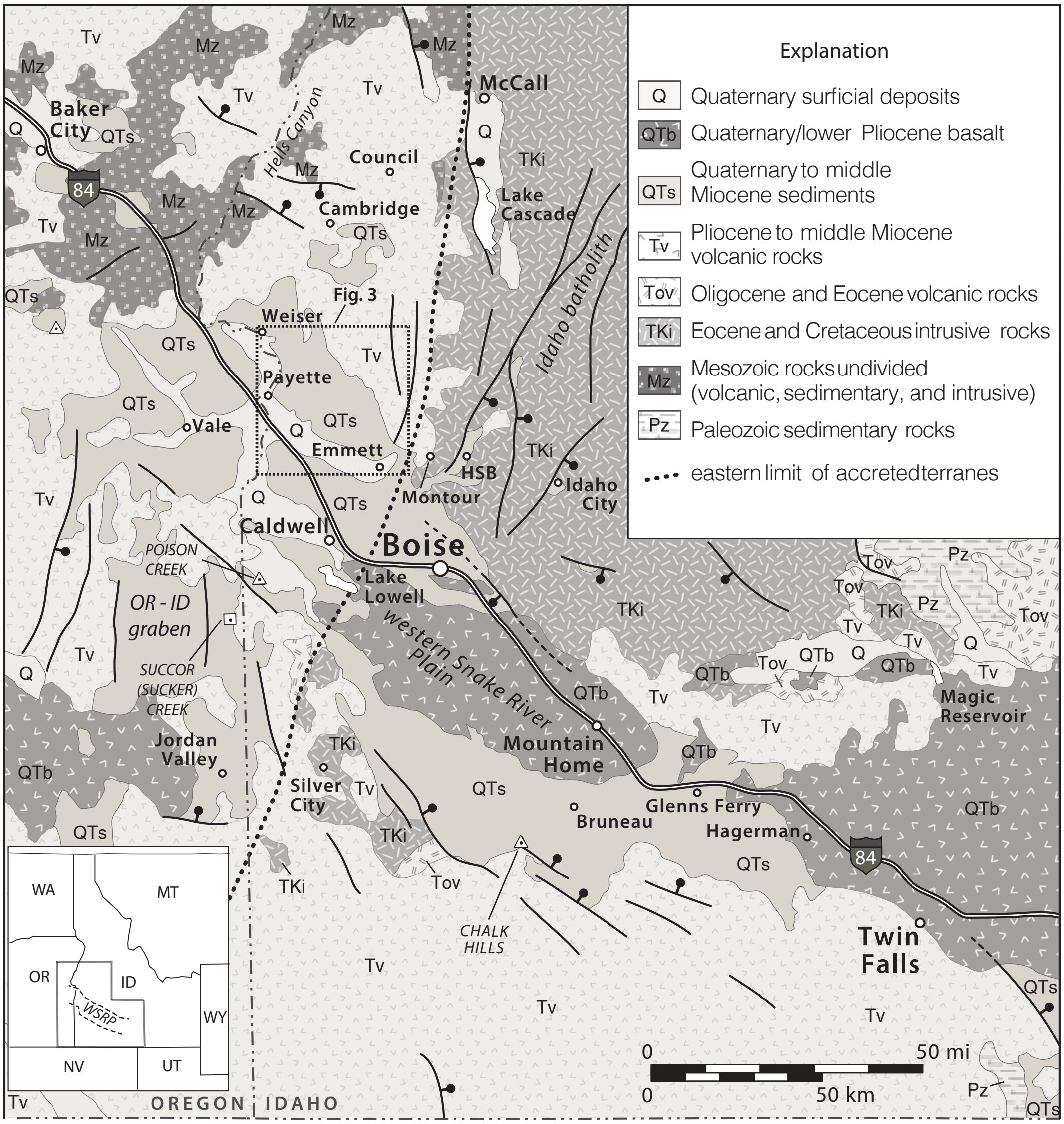


Figure 1. Simplified geologic map of southwest Idaho and southeast Oregon showing the distribution of Quaternary and Tertiary volcanic and sedimentary strata, Eocene and Cretaceous intrusive rocks, and older Mesozoic to Paleozoic strata. CHALK HILLS = Chalk Hills Formation of the Idaho Group; POISON CREEK = Poison Creek Formation of the Idaho Group; SUCCOR CREEK = Succor Creek Formation; HSB = Horseshoe Bend, Idaho.

Formations and the Pliocene–early Pleistocene Glenns Ferry Formation (Buwalda, 1923; Malde and Powers, 1962). Previous research has focused on the area south of the Snake River, particularly the well-exposed sections of the Poison Creek, Chalk Hills, and Glenns Ferry Formations near Bruneau, Idaho (e.g., Kimmel, 1979, 1982; Swirydczuk, 1979, 1980; Smith et al., 1982), and the older Succor Creek Formation (spelled 'Sucker Creek' in some reports) southwest of Homedale (e.g., Lindgren, 1898; Smith 1938; Chaney and Axelrod, 1959; Graham 1963; Axelrod, 1964; Taggart et al., 1980; Lawrence, 1988; Taggart and Cross, 1990; Downing and Swisher, 1993; Fields, 1996). This study area (designated in Fig. 3) has received recent attention, because it is the focus of hydrocarbon production that began in 2010. By the end of 2022, a total of 24 wells had been drilled (Fig. 3), and 19 of them produced hydrocarbons.

We present a summary of results from geologic mapping initiated in 2013 by the Idaho Geological Survey (IGS) and funded in part by the STATEMAP component of the U.S. Geological Survey's National Cooperative Geologic Mapping Program (e.g., Feeney et al., 2018;

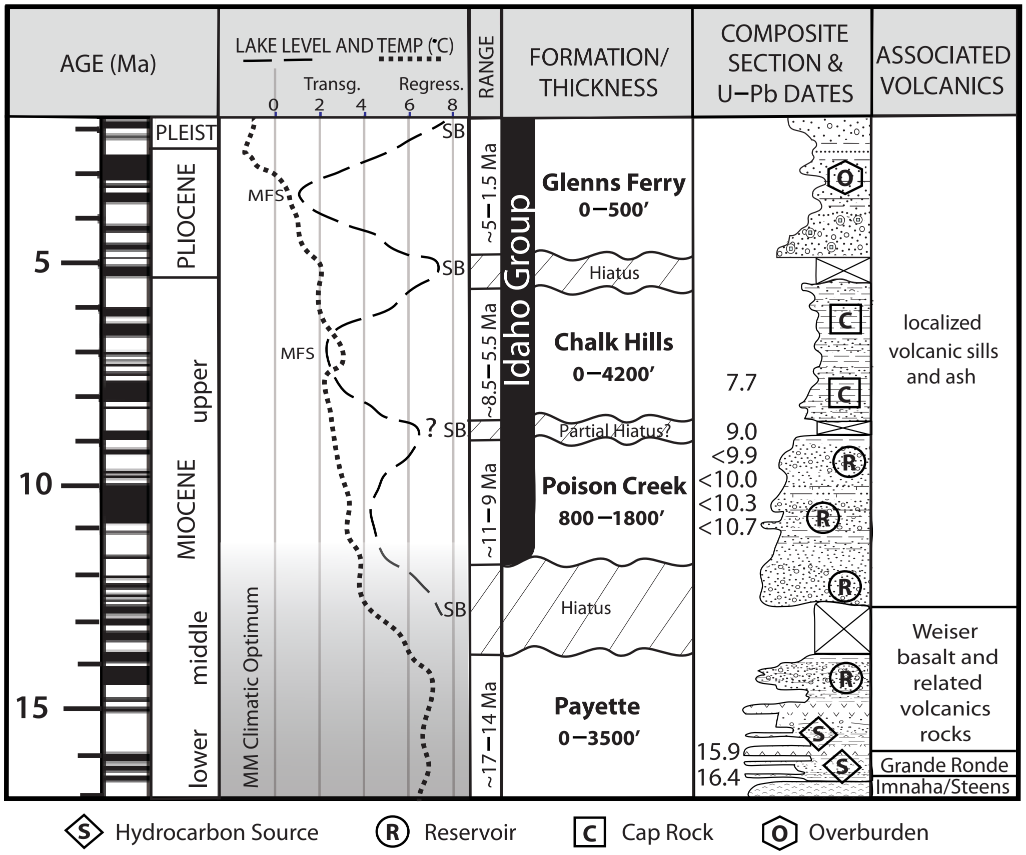


Figure 2. Regional stratigraphy and graphical composite stratigraphic section of the Glenns Ferry, Chalk Hills, Poison Creek, and Payette Formations north of the western Snake River Plain (WSRP). Locations of U–Pb ages are in Table 1. Compiled from Wood (1994), Haq et al. (1987), Zachos et al. (2001), Wood and Clemens (2002), and Reidel et al.

Feeney et al., 2023; Lewis et al., 2023; Love et al., 2023). Mapping was augmented by palynomorph correlation (by R. Love), and zircon U–Pb age determinations of silicic volcanic rocks (by M. Schmitz). A primary goal of this work is the reconciliation of prior stratigraphic interpretations with IGS mapping, paleobotany, and geochronology. The mapping is designed to give an updip perspective on the new hydrocarbon fields. In addition, a better understanding of the stratigraphy is considered valuable for potential hydrogeologic studies related to hydrocarbon extraction. This work also has regional paleoclimate significance as the sedimentary sequence was deposited contemporaneously with part of the global mid-Miocene climatic optimum (Zachos et al., 2001, 2008; Kasbohm and Schoene, 2018). Mapping and basin characterization studies are ongoing, supported by whole-rock X-ray fluorescence (XRF) geochemical analyses of volcanic rocks, U–Pb zircon dating, and sequence stratigraphy (Barton, 2019).

GEOLOGIC SETTING, STRATIGRAPHY, AND HYDROCARBON EXPLORATION

Basin Architecture

The oldest faults in the area are north–south-striking normal faults related to the larger western Idaho fault system (Figs. 1 and 3) and the Oregon-Idaho graben (Capps, 1941; Fitzgerald, 1982; Knudsen et al., 1996, Cummings et al., 2000), which are interpreted to have provided initial basin accommodation for accumulation of the Payette Formation, Succor Creek Formation, and related Miocene strata. Offsets of ash found in surficial fan deposits along the Ola Valley fault (formerly Squaw Creek fault) as well as offsets seen in National Agriculture Imagery Program- and LiDAR-derived imagery along west Ola Valley and Big Flat indicate activity on these north–south-striking faults into the Holocene (Gilbert et al., 1983). The second major faulting regime in the area consists of northwest-striking normal faults, including the Paddock Valley fault system (Fitzgerald, 1982; Fig. 3), which were active from roughly 12 to 5 Ma during and following sediment deposition. These are part of a larger system related to the formation of the WSRP. Sediments deposited in both the north–south system and the northwest–southeast system are collectively referred to as the "basin" in this paper, although details and timing of component basins are not well understood at this time. Subsidence of this unnamed basin (it has informally been referred to as Payette basin, Weiser basin, and others depending on the area included) has resulted in the current geometry, whereby the strata in the mapped area have an overall southwest dip (Figs. 3 and 4). We did not find evidence of a basin-margin fault.

Miocene and Younger Volcanism

The early Miocene in northern Nevada, southeast Oregon, and southwest Idaho was host to the coeval appearance of bimodal volcanism related to the Yellowstone hotspot and the flood basalts of the Columbia River Basalt Group (CRBG) (Swanson et al., 1979; Reidel et al., 1989; Smith and Braile, 1994; Camp and Ross, 2004; Benson et al., 2017). Bimodal volcanism of the Yellowstone hotspot began at ~16.5 Ma in eastern Oregon and northern Nevada (Pierce and Morgan, 1992; Cummings et al., 2000; Ferns and McClaughry, 2013; Streck et al., 2015; Ferns et al., 2017; Mahood and Benson, 2017). The CRBG initiated at 17.23 Ma with the Picture Gorge Basalt erupting in eastern Oregon (Cahoon et al., 2020) and was followed at 16.6 Ma by the Steens Basalt in southeast Oregon (Camp et al., 2013). The main phase of volcanism including the Imnaha Basalt, Grande Ronde Basalt, and Wanapum Basalt was then emplaced in northeastern Oregon, southeastern Washington, and western Idaho (Hooper et al., 2007; Barry et al., 2013). Recent U–Pb zircon dates from interbedded tuffs indicate that 95% of the CRBG volume erupted from 16.7 Ma to 15.9 Ma (Kasbohm and Schoene, 2018).

Volcanism north of the WSRP (Figs. 1 and 3) includes marginal flows of the Steens, Imnaha, and Grande Ronde Basalts of the CRBG. The CRBG is unconformably overlain by the Weiser volcanic field (WVF) and silicic ash fallout from regional volcanism (Fitzgerald, 1982; Feeney et al., 2017) that erupted from 15.5 Ma to 14.9 Ma (M. Schmitz, personal communication, 2018; Feeney and Schmidt, 2019). The thickest exposure of the WVF is 1,640 ft (500 m) northeast of the Weiser River, but the base is not exposed (Garwood et al., 2014). This thickness includes Payette Formation sedimentary interbeds. Likewise, the underlying CRBG flows are also interbedded with the Payette Formation. The WVF flows thin southward to Paddock Valley Reservoir, and are absent south of it (Fig. 3).

The youngest volcanism in the region is the late Tertiary to Quaternary WSRP style of volcanism (QTb on Fig. 1), which includes lava flows, cinder cones, shield volcanoes, and maar-like vents erupting onto wet sediments and Snake River Plain fluvial gravels (Shervais et al., 2002; Bonnichsen et al., 2016; Rivera et al., 2021).

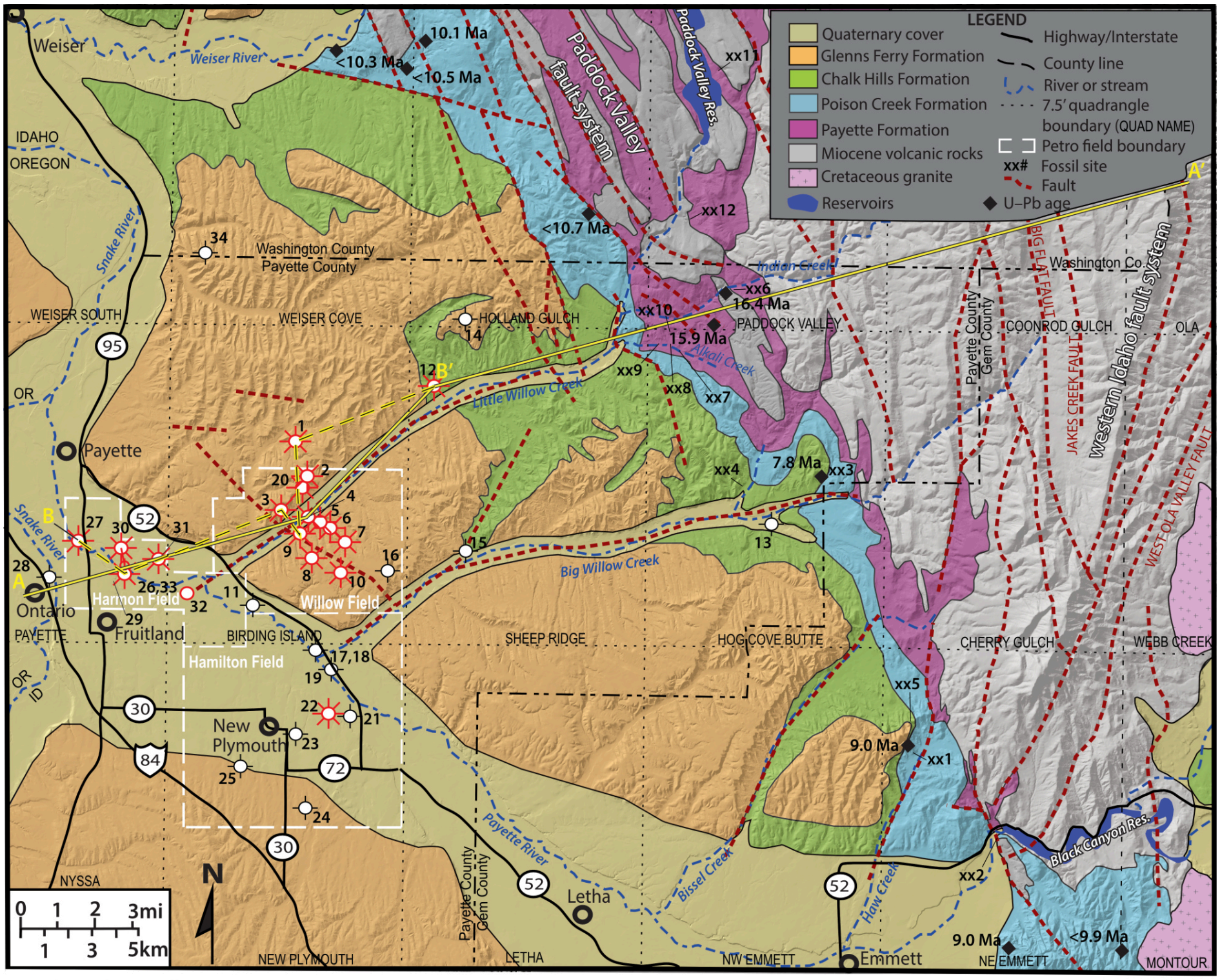
Early Sedimentation: Payette Formation

The CRBG and rhyolitic volcanism created a new landscape that changed the drainage patterns and resulted in a series of small lakes and fluvial watersheds throughout the Inland Northwest.

The sedimentary deposits formed in this landscape are now represented by the age-correlative (1) Latah Formation of eastern Washington and northern Idaho (Pardee and Bryan, 1926; Kirkham and Johnson, 1929; Smiley, 1989; Smiley and Rember, 1985); (2) the Succor (Sucker) Creek Formation of southeast Oregon and southwest Idaho (Taggart et al., 1980; Fields, 1996; Nash and Perkins, 2012); (3) the Payette Formation of southwestern Idaho (Lindgren, 1898; Bowen, 1913; Buwalda, 1924; Kirkham, 1931); and (4) the Mascall Formation of central Oregon (Bestland et al., 2008). These units were deposited during and after the mid-Miocene climatic optimum, which lasted from ~17–14 Ma (Zachos et al., 2001, 2008; McKay et al., 2014), and it has been suggested that CRBG eruptions may have played a role in development of the climatic optimum (Kasbohm and Schoene, 2018). The Payette Formation (early–middle Miocene) is the oldest sedimentary unit in the basin (Figs. 2, 3, and 4), and is likely a contributor as the main hydrocarbon source and reservoir for the oil and gas play (Washburne, 1911; Warner, 1975; Bond et al., 2011).

The Payette Formation was originally defined by Lindgren (1898), who noted that it was typically deformed and overlain by the less-deformed Idaho Formation (now the Idaho Group; Fig. 2). The relationship of the Payette Formation to the CRBG has been uncertain. Several authors, including Lindgren (1898), have suggested that the Payette Formation is interbedded with and overlies the CRBG. In contrast, Kirkham (1931) suggested that the Payette Formation should only include the interbeds within the volcanic rocks and those that underlie them whereas the sedimentary package above should be regarded as the Idaho Group. These volcanic deposits include basaltic to andesitic tholeiites of the CRBG, and what is now known as basaltic to rhyolitic calc-alkaline rocks of the WVF (Fitzgerald, 1982; Reidel et al., 2013).

The age of the lower part of the Payette Formation can be constrained by the age of the dated volcanic units with which it is interbedded, including the 16.9 and 15.9 Ma eruption age of the CRBG, and the 15.4 to 14.9 Ma flows



Hydrocarbon Wells

Producing | Plugged and Abandoned | Drilled/confidential

1 Kauffman 1-34
2014, TD 5,800′

2 ML Investments 1-3
2015, TD 5,585′

3 Kauffman 1-9
2014, TD 5,766′

4 ML Investments 1-10
2010, TD 6,800′

5 ML Investments 2-10
2013, TD 4,996′

6 ML Investments 1-11
2014, TD 5,500′

7 DJS Properties 2-14
2014, TD 5,500′

8 DJS Properties 1-15
2010, TD 6,288′

9 ML Investments 3-10
2018, TD 5,000′

10 DJS Properties 1-14
2010, TD 6,272′

11 Smoke Ranch 1-21
2013, TD 5,088′

12 Island Capital 1-19
2010, TD 4,385′

13 Schwarz #1-10
2010, TD 2,602′

14 Assmussen 1
1956, TD 4,015′

15 Reins No. 2
1975, TD 4,855′

16 Boise Petroleum No. 1
1931, TD 2,500′

17 Virgil Johnson #1
1955, TD 4,040′

18 Virgil Johnson #2
1955, TD 3,522′

19 Ted Daws #1
1955, TD 1,679′

20 ML Investments 2-3
2015, TD 5,034′

21 Espino 1-2
2010, TD 4,500′

22 Tracy Trust 3-2
2010, TD 2,815′

23 White 1-10
2010, TD 2,415′

24 Korn 1-22
2010, TD 2,324′

25 State 1-17
2010, TD 4,519′

26 Barlow 1-14
2018, TD 4,150′

27 Fallon 1-10
2018, TD 4,519′

28 Ore-Ida No. 1
1979, TD 10,040′
(geothermal)

29 Barlow 2-14
2021, TD 4,575′
(directional 803′ to SW)

30 Fallon 1-11
2021, TD 5,456′
(directional 1,702′ to S)

31 Dutch Lane 1-13
2022, TD 4,875′
(directional 677′ to ESE)

32 Irvin 1-19,
2022 drilled/confidential
TD 5,500′

33 Barlow 3-14, 2022,
drilled/confidential,
TD 5,028′

34 Daniels No. 1
(Crystal Dome)
1930, TD 1,895′

Figure 3. Study area with mapped geology and sample locations for U–Pb ages and fossil localities. Grid lines in background refer to quadrangle boundaries. Refer to Table 1 for age information and Table 3 for more detailed description of fossil locality. Note A-A′ (solid line) for cross section in Figure 4, and B-B′ (dashed line) for correlated well traverse in Figure 10.

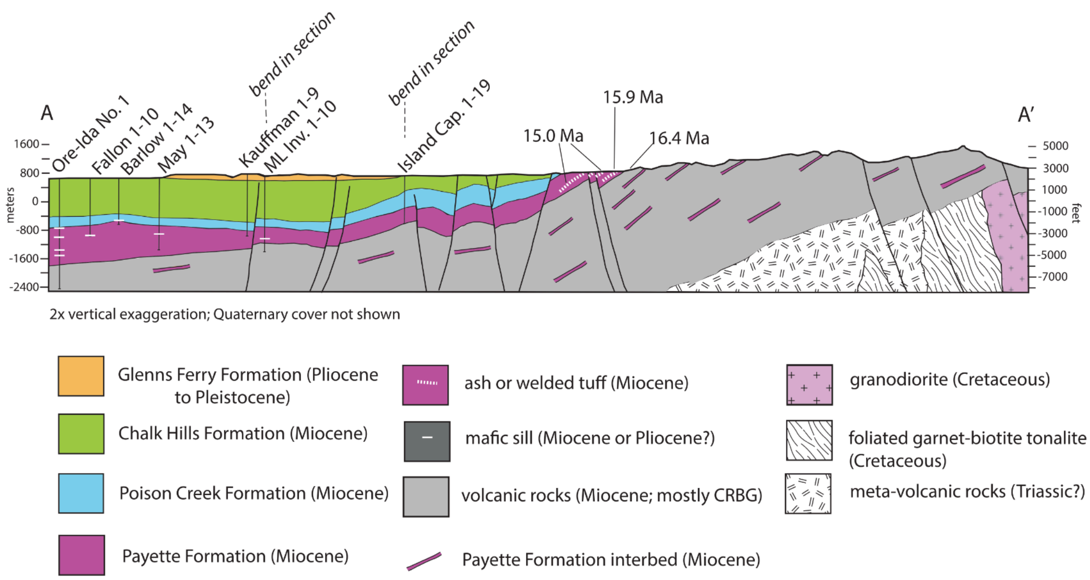


Figure 4. Cross section A–A' from the Ore-Ida well east-northeast to the edge of the Idaho batholith. West-southwest part of the section is based on well data; east-northeast part is based only on surface mapping and dip projection. ML Inv. = ML Investments; Island Cap. = Island Capital; CRBG = Columbia River Basalt Group.

of the WVF (Jarboe et al., 2010; Kasbohm and Schoene, 2018; Feeney and Schmidt, 2019). The minimum age is not well constrained, but is ~14 Ma (Breedlovestrout and Lewis, 2017; Breedlovestrout et al., 2017).

Idaho Group Sedimentation: Poison Creek, Chalk Hills, and Glenns Ferry Formations

Following a hiatus after the deposition of the Payette Formation, accommodation for the Idaho Group sediments is associated with the rifting and subsidence of the northwest-trending WSRP that resulted in a series of paleolakes. The late Miocene to Pliocene Idaho Group was deposited in a largely lacustrine environment called ancient 'Lake Idaho' by Cope (1883). At its greatest extent, Lake Idaho spanned several thousand km^2 (Kimmel, 1982; Viney et al., 2017). Abundant tephra are incorporated into the Idaho Group as primary ash falls or eroded from adjacent highland, particularly in the Chalk Hills Formation. Much of the tephra likely originated to the east and southeast during extrusion of the silicic volcanic rocks associated with the Yellowstone hotspot track (Tv on Fig. 1).

Average global temperatures declined from ~16.5°C at 13 Ma to ~10°C at 9 Ma, near the end of the deposition of the Poison Creek Formation (Wolfe, 1995; Zachos et al., 2001, 2008; Buechler et al., 2007). By late Miocene to Pliocene, the global temperatures had cooled, and the region became drier. The deciduous trees that were once common became rare. Dryland sagebrush, saltbrush, herbaceous flowering plants, and more sparsely spaced conifers dominated the landscape.

Regionally, the Cascade Range most likely reached current elevations in the early Pliocene following rapid uplift in the late Miocene (Mackin and Cary, 1965; Ashwill, 1983; Kohn et al., 2002; Reiners et al., 2002; Mitchell and Montgomery, 2006). Mustoe and Leopold (2014) used fossil microfloras to estimate that the uplift of the Cascade Range occurred between ~8 and 6 Ma. They concluded that a 30 to 50% drop in mean annual precipitation occurred from ~12 Ma to ~3.4 Ma due to a combination of the rapid uplift of the Cascades and globally widespread climate trends. The drier paleoclimatic conditions are recorded in the (1) lower–middle Idaho Group (Malde and Powers, 1962; Kimmel, 1982; Swirydczuk et al., 1982; Smith and Cossel, 2002; Wood and Clemens, 2002); (2) 12 to 7.4 Ma Ellensburg Formation of central Washington (Smiley, 1963; Bingham and Grolier, 1966; Smith 1988a, 1988b; Smith et al., 1989); (3) 11.5 Ma Trapper Creek flora (Axelrod, 1964; Davis and Ellis, 2010); (4) 10.5 to 8.5 Ma Pickett Creek flora of Owyhee County, Idaho (Buechler et al., 2007); and (5) ~7 Ma Rattlesnake Formation of central Oregon (Dillhoff et al., 2009).

Where Buwalda (1923) defined the type section of the Poison Creek Formation, along the Poison Creek Grade Road (Fig. 1), the thickness of the entire section was less than 100 ft (30 m). Malde and Powers (1962) accepted Buwalda's designation, and suggested that a thicker section (at least 400 ft [122+ m]) occurred east of the Reynolds

Creek Road northwest of Murphy and southeast of the type Poison Creek Formation. Savage (1961) used the term 'Poison Creek Formation' in the Emmett area, but did not notice a striking difference from the overlying Idaho Group. Smith and Cossel (2002) used the 'Poison Creek Formation' designation for the deposits south of the Snake River Plain and suggest that unconformities bound the formation above and below. Their fish biostratigraphy indicates that the Poison Creek Formation was deposited during the Clarendonian North American Stage (13.6 to 10.3 Ma), and could be as young as 9.0 Ma.

Malde and Powers (1962) named the 'Chalk Hills Formation' for the rocks exposed in the badlands in the southeast part of the WSRP southwest of Bruneau (Fig. 1). Some authors have suggested that the lowermost Chalk Hills Formation may have been deposited in a series of lakes (Mustoe and Leopold, 2014; Viney et al., 2017). Kimmel (1982) suggested that the Chalk Hills lakes were interconnected, and Malde and Powers (1962) suggested that the Chalk Hills deposits have lateral continuity and were most likely deposited in a continuous shallow lake with intermittent stream inputs. Most likely, by the time the middle to upper Chalk Hills Formation was deposited, one single enormous lake persisted throughout the WSRP (Wood and Clemens, 2002).

Regionally, the base of the Chalk Hills Formation is thought to have been deposited between 9 and 8 Ma (Armstrong et al., 1975; Kimmel, 1982; Smith and Cossel, 2002; Viney et al., 2017), whereas the top was deposited between 5.9 and 5.5 Ma (Kimmel, 1982; Smith et al., 1982; Perkins et al., 1998; Smith and Cossel, 2002; Wood and Clemens, 2002). Neither the maximum nor minimum ages are well constrained, and the formation may be bounded by variable unconformable surfaces in different parts of the basin (Wood, 2004). Although the cause of the regression, i.e. lowering of the lake, at the end of the Chalk Hills Formation deposition is unclear, Wood and Clemens (2002) suggested that the regressive lowstand is marked with a hiatus in deposition between 6 and 4 Ma.

The Glenns Ferry Formation represents the last stage of ancient Lake Idaho (Figs. 2, 3, and 4), which was deposited as drying and cooling of the paleoclimate continued. The basal deposits of the Glenns Ferry Formation are separated from the Chalk Hills Formation by a slight angular unconformity marking a hiatus that represents a period of regression in the lake and low water levels (Wood and Clemens, 2002). Deposition of the Glenns Ferry Formation began sometime between ~5.5 Ma and ~4 Ma (Malde, 1972; Kimmel, 1982; Smith et al., 1982; Perkins et al., 1998; Smith and Cossel, 2002; Wood and Clemens, 2002). Above the base, a time-transgressive oolitic marker bed (Malde and Powers, 1962; Swirydczuk et al., 1980) is mapped to the southeast near Emmett (Wood and Clemens, 2002; Feeney et al., 2018). Locally, the oolite and coarse sandstone contain fish fossils (Swirydczuk et al., 1980; Kimmel, 1982). Oolite lenses occur discontinuously in sandstone around the margins of the WSRP. These are interpreted as a "bathtub ring" of transgressive beach deposits as Lake Idaho became an alkaline closed-lake basin near a relative highstand (Warner, 1975; Swirydczuk et al., 1979; Wood and Clemens, 2002; Wood, 2004).

The 'Glenns Ferry Formation' was named from the type section west of Hagerman, Idaho (Malde and Powers, 1962; Fig. 1). Pliocene to Pleistocene in age, it has paleomagnetic ages of 3.79, 3.32, and 3.09 Ma near the Horse Quarry of the Hagerman Fossil Beds National Monument (Nelville et al., 1979; Mustoe and Leopold, 2014). The age of the Glenns Ferry Formation is 4.2 to 3.2 Ma to the east of Hagerman (Izett, 1981; Hart and Brueseke, 1999; Link et al., 2002), and as young as 1.67 to 1.5 Ma to the west near Caldwell (Repenning et al., 1995). The volcanic unit that overlies the Glenns Ferry Formation (termed the 'basalt of Pickles Butte' in Othberg, 1994) was dated using $^{40}Ar/^{39}Ar$ geochronology at 1.67 Ma. This date and emplacement of the basalt indicates that ancient Lake Idaho drained by that time (Othberg, 1994; Wood and Clemens, 2002). The demise of Lake Idaho occurred after the Snake River drainage was captured into the Columbia River drainage (~2.7 to 2 Ma) at a low point near Huntington, Oregon. This resulted in the downcutting of Hells Canyon of the Snake River (Wheeler and Cook, 1954; Malde, 1991; Othberg, 1994; Hearst, 1999; Smith et al., 2000; Wood and Clemens, 2002 [see Fig. 1 for location of Hells Canyon]).

Hydrocarbon Exploration and Production

The earliest hydrocarbon exploration of the basin began in 1902 in Ontario, Oregon, when a 215 ft (66 m) water well produced flammable gas (Washburne, 1911). A well drilled in 1907 at Payette, Idaho, struck gas at 740 ft (226 m), and this resulted in a water and debris blowout. A subsequent well near the Ontario site contained gas at 1,058–1,066 ft (322–325 m) and again at 2,199 ft (670 m) (Washburne, 1911). Washburne (1911) reported that when the valve was opened, gas flowed with a "roar," but dwindled in 30 minutes. Between 1928 and 1930, several wells in the vicinity of Payette had gas blowouts from sands above a depth of 1,700 ft (518 m), and some samples tested 1,624 British thermal units (Btu) and reported ethane contents of 25 to 70%. Northeast of Payette, the 1930 Crystal Dome well encountered gas at 1,580 ft (482 m) and 1,865 ft (568 m), blew out before it collapsed, and had an estimated short-lived flow of 10,000 Mcf of natural gas per day (one thousand cubic feet/day). The Boise Petroleum No. 1 well was drilled in 1931 and indicated a gas odor with a note that they "could probably have capped the hole and lit the gas." The 1955 Virgil Johnson #1 well northeast of New Plymouth hit gas at 1,382 ft (421 m), and tested 400 Mcf/d for a short time before collapsing.

Based largely on 2D seismic data reprocessed from the 1971–72 Chevron's WSRP acquisition, Bridge Resources Corp. drilled 11 wells in 2010. The ML Investments 1-10 discovery well on Little Willow Creek (Fig. 3) tested 6,000 Mcf/d of gas and 100 barrels/day (bbls/d) of 64° API condensate from sand at 4,100 ft (1,250 m) depth, establishing the Willow field. The Espino 1-2 well tested 28–72 Mcf/d and 1 bbl/d of condensate and State 1-17 well tested 537 Mcf/d of dry gas, both from sands 1,400–2,300 ft (427–701 m) deep. These two wells established the Hamilton field. Although some initial wells tested ~500 Mcf/day, the flows were not sustained, and they are not considered economic. In 2012, Alta Mesa Services LP acquired the wells and leases of Bridge Resources Corp., collected 338 mi^2 of 3D seismic data, and drilled seven wells in the Willow field targeting the laterally continuous sands that were originally discovered in ML Investments 1-10. From 2013 to 2016, gas from State 1-17 well sourced the nearby town of New Plymouth at ~9–30 Mcf/d.

In 2015, a pipeline and processing plant were completed, and ~7,000 Mcf/d were produced from the Willow field along with ~100 bbls/d of condensate. Barlow 1-14 wildcat, drilled in 2018, tested 1,775 Mcf/d of gas and 30 bbls/d of condensate from a depth of 3,503 ft (1,068 m), and this well established the Harmon field (Fig. 3). In 2020, Snake River Oil and Gas Inc. acquired the wells and leases of Alta Mesa Services LP. The aforementioned pipeline connected the Harmon field well to the processing plant, and production began in 2020. Five more wells were drilled in the Harmon field. November 2022 production from sands 3,400–3,960 ft (1,036–1,207 m) deep were 7,800 Mcf/d gas and 120 bbls/d of condensate, largely supplanting the dwindling production from the Willow field wells.

METHODS

Geologic mapping at 1:24,000 scale was conducted in 14 U.S. Geological Survey 7.5′ quadrangles, and are posted on the Idaho Geological Survey website (www.idahogeology.org). Field work was augmented with whole-rock XRF geochemical analyses of volcanic rocks at Franklin & Marshall College, Lancaster, Pennsylvania, and the results are reported on the published maps. Silicic tuffs were targeted for U–Pb zircon dating to provide age constraints for the sedimentary units. All sample preparation and analytical measurements were performed in the Isotope Geology Laboratory at Boise State University (Table 1). Zircon concentrates were obtained via crushing, and then isolated from the host rock using standard density and magnetic separation techniques. Zircons were then treated in a muffle furnace at 900°C for 60 hours in quartz crucibles to anneal minor radiation damage and enhance cathodoluminescence (CL) emission (Nasdala et al., 2002). This technique promotes more reproducible interelement fractionation during laser ablation (Allen and Campbell, 2012), and prepares the crystals for subsequent chemical abrasion (Mattinson, 2005). Following annealing, individual grains were hand-picked and mounted, polished, and imaged by cathodoluminence (CL) on a scanning electron microscope. For some samples, the polished zircons were then analyzed by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) using a New Wave Research UP-213 Nd:YAG deep UV (213 nm) laser ablation system coupled to a Thermo Scientific XSERIES Quadrupole ICP-MS following methods described in Macdonald et al. (2018). Based on LA-ICP-MS $^{206}Pb/^{238}U$ ages, elemental data, and CL zoning patterns, subsets of zircons from each sample were plucked from the epoxy and then subjected to a modified version of the chemical abrasion method of Mattinson (2005). Single crystal fragments plucked from grain mounts were individually abraded in a single step with concentrated HF at 190°C for 12 hours.

Chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) analyses were performed on an IsotopX IsoProbe-T multicollector mass spectrometer following procedures described in detail in Macdonald et al. (2018). U–Pb ages and uncertainties for each analysis were calculated using the algorithms of Schmitz and Schoene (2007) and the U decay constants of Jaffey et al. (1971). All geological ages are interpreted from the weighted means of multiple single crystal $^{206}Pb/^{238}U$ dates, and the errors for these ages are reported at the 95% confidence interval in the form of ± X(Y)[Z] where: (1) X is the internal standard deviation multiplied by the Student's t-distribution multiplier for a two-tailed 95% critical interval and n minus 1 degree of freedom, and by the square root of the reduced chi-squared parameter (or mean squared weighted deviation [MSWD] (Wendt and Carl, 1991); (2) Y is this analytical uncertainty combined with the uncertainty in the EARTHTIME 535 mixed U–Pb tracer calibration (0.03%; Condon et al., 2015; McLean et al., 2015); and (3) Z convolves the ^{238}U decay constant uncertainty (0.018%; Jaffey et al., 1971) with the uncertainty in Y. Dating results are summarized in Table 1. The full isotopic data and interpreted ages are presented in Supplemental Table 1.

Palynomorphs were extracted and analyzed from surface samples and well cuttings from five of the initial Bridge Resources Corp. and Paramax Resources Ltd. exploratory wells by author R. Love. Samples were

Table 1. Summary of chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) U–Pb isotopic results and location information for zircons from silicic volcanic rocks collected near Emmett, Idaho.

Sample/ Location	Formation and lithology	Latitude (NAD27)	Longitude (NAD27)	Age interpretation U–Pb zircon (CA-IDTIMS)
16RLB014 Sulfur Gulch	Chalk Hills Formation; rhyolitic pumice	44.0690	-116.5350	Depositional age from weighted mean $^{206}Pb/^{238}U$ date = 7.776 ± 0.013 Ma (95% c.i.); MSWD = 0.54 (n=8)
15RL015a Haw Creek	Poison Creek Formation; rhyolitic pumice	43.9642	-116.4879	Depositional age from weighted mean $^{206}Pb/^{238}U$ date = 9.005 ± 0.015 Ma (95% c.i.); MSWD = 0.43 (n=6)
15RL014 E of Emmett	Poison Creek Formation; rhyolitic lapilli tuff	43.8866	-116.4343	Depositional age from weighted mean $^{206}Pb/^{238}U$ date = 9.041 ± 0.016 Ma (95% c.i.); MSWD = 0.86 (n=8)
14RL065 SW of Montour	Poison Creek Formation; rhyolitic lapilli tuff	43.8837	-116.3708	Maximum depositional age from youngest $^{206}Pb/^{238}U$ date = 9.896 ± 0.022 Ma (95% c.i.)
21DF759 S. Crane Road	Poison Creek Formation, fine white ash bed	44.2367	-116.7436	Depositional age from weighted mean $^{206}Pb/^{238}U$ date = 10.051 ± 0.007 Ma (95% c.i.); MSWD = 1.01 (n=6)
19DF691 Sunnyside Canal	Poison Creek Formation; 0.5 m thick gritty white ash bed	44.2326	-116.7914	Maximum depositional age from youngest $^{206}Pb/^{238}U$ date = 10.054 ± 0.063 Ma (95% c.i.)
19MB002 Cove Rd. & S. Crane Rd. intersection	Poison Creek Formation; thin fine white ash bed	44.2266	-116.7557	Maximum depositional age from youngest $^{206}Pb/^{238}U$ date = 10.498 ± 0.065 Ma (95% c.i.)
21DF744 lower Holland Gulch	Poison Creek Formation; thin white tuff bed	44.1708	-116.6564	Maximum depositional age from youngest $^{206}Pb/^{238}U$ date = 10.660 ± 0.032 Ma (95% c.i.)
15DF415 Indian Creek	Payette Formation; dacitic lapilli tuff	44.1731	-116.5899	Depositional age from weighted mean $^{206}Pb/^{238}U$ date = 15.882 ± 0.020 Ma (95% c.i.); MSWD = 1.84 (n=4)
16DF438 Indian Creek	Rhyolite of Indian Creek; rhyolitic flow	44.1403	-116.5865	Depositional age from weighted mean $^{206}Pb/^{238}U$ date = 16.395 ± 0.009 Ma (95% c.i.); MSWD = 0.72 (n=9)

processed by Global Geolab Ltd. in Medicine Hat, Alberta, Canada. Five grams of each sample were washed, crushed, macerated in hydrochloric acid and hydrofluoric acid, oxidized, sieved, and separated from the clay grains. The palynomorph slides were examined and photographed under 1000× power under a transmitted light microscope. Index palynomorphs were then identified stratigraphically to show presence versus absence.

RESULTS

Mapping and Geochronology

The Payette Formation east of Payette consists of mudstone with lesser amounts of weakly consolidated to highly silicified sandstone to granule conglomerate (Fig. 5). Ash beds are common, and can occur as thin synchronous beds or thick reworked deposits. Diatoms are locally present in the finer grained beds. Mudstones are brown and green, have high bentonite content, and weather to a "badlands" topography and appearance. The Payette Formation locally contains higher concentrations of organic matter than the overlying Poison Creek, Chalk Hills, and Glenns Ferry Formations, but the organic content in the Payette Formation is still sparse in surface exposures. In the Alkali Creek area, northwest of Emmett, the maximum thickness of the Payette Formation is estimated at ~2,300 ft (~700 m) based on our mapping (Lewis et al., 2023; Love et al., 2023). The Payette Formation interbedded with and above the section near the Oregon border may be as thick as thick as ~3,500 ft (~1,050 m) as shown in our regional cross section (Fig. 4). Regional marker beds are volcanic ashes

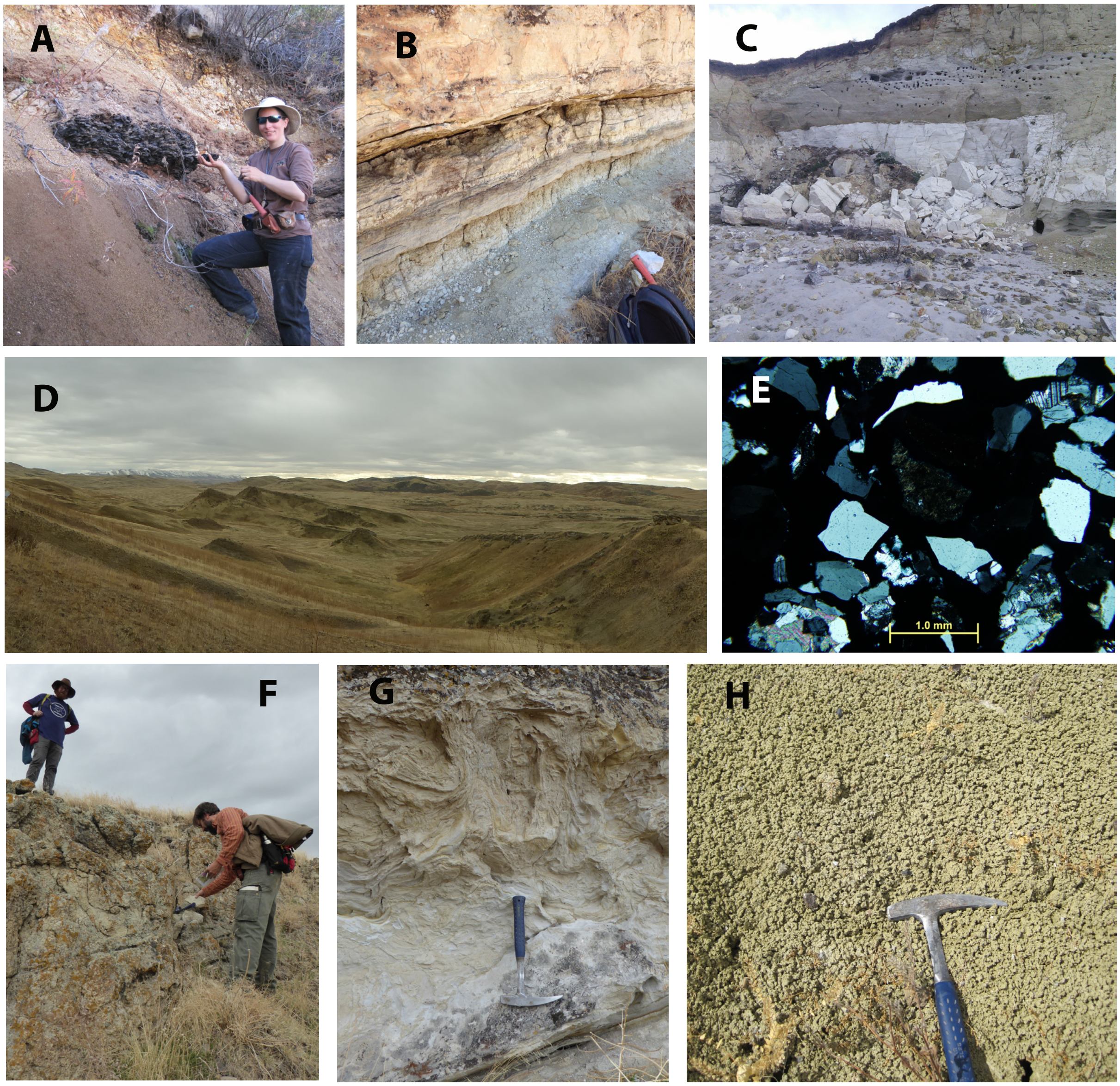


Figure 5. Photographs of field outcrops, thin sections, and hand samples for the Payette Formation. **A,** Indian Creek lignite in southeast Paddock Valley Reservoir 7.5′ quadrangle. **B,** Ash containing localized ostracods in Alkali Creek, Paddock Valley Reservoir 7.5′ quadrangle. **C,** Ash and sandstone south of Crane Creek Reservoir, ~10.5 km north of Paddock Valley Reservoir. **D,** Looking southeast at the Alkali Creek drainage basin in the Hog Cove Butte 7.5′ quadrangle, showing the general southwest downwarp of the sediments. **E,** Sandstone in the well cuttings of ML Investments 1-10 at 6,280’ MD. **F,** Lapilli-rich, unwelded tuff south of Indian Creek in the Paddock Valley Reservoir 7.5′ quadrangle, dated at 15.88 Ma. **G,** Soft-sediment folds in ostracod-bearing ash north of Alkali Creek. **H,** Characteristic “popcorn” weathering in the Hog Cove Butte 7.5′ quadrangle.

with specific geochemical signatures that can be mapped laterally (Nash and Perkins, 2012). Dip changes indicate an unconformity between the Payette Formation and the overlying Lake Idaho sedimentation. The formation thins to the southeast toward Emmett and northwest toward the Weiser River by an erosional contact (Fig. 3).

Two high-precision U–Pb zircon age determinations from the Alkali Creek area north of Emmett provide important constraints on the age of Payette Formation sedimentation (Fig. 6 and Table 1; Feeney et al., 2023). The oldest age (sample 16DF438) is from the rhyolite of Indian Creek in the southern part of the Paddock Valley Reservoir

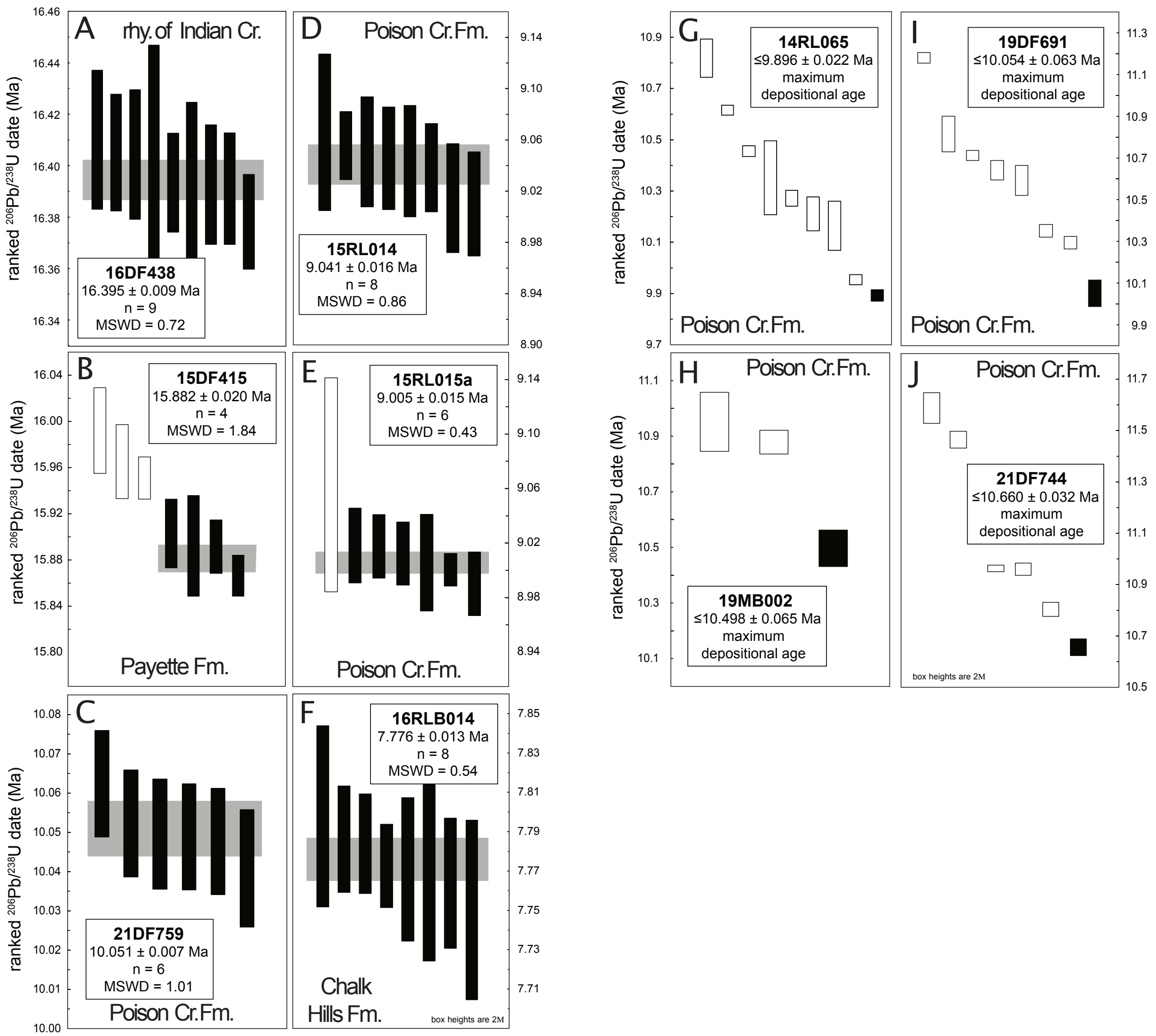


Figure 6. Plot of $^{206}Pb/^{238}U$ ages from grains of zircon in ash deposits from the Payette/Emmett area analyzed by CA-ID-TIMS. Plotted with Isoplot 3.0 (Ludwig, 2003). **A–F,** Depositional ages of ash beds. Error bars are at 2σ. Weighted-mean dates are shown and represented by gray boxes behind the error bars. White boxes represent dates not used in weighted-mean calculations. **G–J,** Maximum depositional ages of ash beds. Black boxes are dates used for maximum depositional age. Error bars are at 2σ. See Table 1 and Supplemental Table 1 for location information and analytical results.

quadrangle (Figs. 3 and 4). This rhyolite is within the lower part of the Payette Formation. It is characterized by < 5% of phenocrysts of plagioclase up to 0.08 in (2 mm) in length in a groundmass of devitrified glass. We dated this rhyolite at 16.395 ± 0.009 Ma based on nine concordant and equivalent single zircon U–Pb analyses (Fig. 6). Overlying the rhyolite of Indian Creek is 100 ft (30 m) of silty claystone, followed by a lapilli-rich unwelded tuff (Fig. 5). Capping the lapilli tuff is a densely welded tuff 3–15 ft (1–5 m) thick. It contains plagioclase and sparse quartz phenocrysts, as well as glass that compositionally is trachydacite (B. Nash, personal communication, 2018). The lapilli contain a few percent plagioclase, and the composition of the glass is 66.9–69.4% SiO_2 and 8.1–9.4% total Na_2O + K_2O (B. Nash, personal communication, 2018). Our new U–Pb zircon geochronology dates this lapilli tuff at 15.882 ± 0.020 Ma (sample 15DF415, Table 1; Feeney et al., 2023), on the basis of four concordant and equivalent single zircon grains. Higher still, roughly 1,600 ft (500 m) above the lapilli ash, is an ostracod-bearing ash layer that is an excellent correlation marker bed.

The Poison Creek Formation east of Payette is dominated by sandstone, but includes some mudstone and ash beds (Fig. 7). The best exposures are east of Emmett where the unit is overall coarser than to the northwest. Sand is arkosic and medium- to coarse-grained, and it contains subangular to subrounded grains of quartz, potassium feldspar, and plagioclase feldspar. In places, it also contains trace amounts of biotite and muscovite. Gravel beds are lenticular channel-fill deposits, 2–13 ft (0.6–4 m) thick of cobble and pebbles of granitic material, felsic dikes, and felsic volcanic rocks. A conspicuous saprolite layer of brown sand, siltstone, and mudstone with root casts marks the top of the formation east of Emmett (Fig. 3), where it is overlain by the Glenns Ferry Formation. Several thick ash beds are present here as well, and a high-precision U–Pb age of 9.041 ± 0.016 Ma was determined from eight concordant and equivalent single zircon dates from a lapilli marker bed (sample 15RL014, Fig. 6 and Table 1; Feeney et al., 2018). The lapilli contain about 2% quartz and 1% sanidine along with obsidian fragments in a rhyolitic matrix (Feeney et al., 2018). Farther to the east, a sample southwest of Montour yielded a maximum depositional age of 9.896 ± 0.022 Ma (sample 14RL065, Fig. 6 and Table 1; Lewis et al., 2016). Exposures north of Emmett near Haw Creek contain sand, siltstone, silty claystone, and claystone, as well as a tephra-rich interval that is 33–65 ft (10–20 m) thick (Feeney et al., 2018, their fig. 3). The base of this interval contains large white pumice blocks up to 6 in (15 cm) in diameter (Fig. 7). Zircons from these pumice blocks yield a U–Pb age of 9.005 ± 0.0015 Ma on the basis of six concordant and equivalent crystals (sample 15RL015a, Fig. 6 and Table 1; Feeney et al., 2018). The pumice contains ~3% sanidine phenocrysts, and whole-rock XRF data reported by Feeney et al. (2018) indicate a rhyolitic composition. This sample came from about 330 ft (100 m) below the base of the Glenns Ferry Formation. Farther northwest, near the mouth of Alkali Creek, the base of the Poison Creek Formation is a thick sand interval overlying the Payette Formation. The sandstone is arkosic and fine- to coarse-grained, and contains subangular to subrounded grains of quartz, potassium feldspar, and plagioclase feldspar. In places, it also contains trace amounts of biotite, muscovite, amphibole, lithic fragments, obsidian, and white volcanic ash. Initially, we tentatively assigned the exposures in the Emmett area to the Chalk Hills Formation (Feeney et al., 2018), but have reconsidered this based on their age and some lithologic similarities to the Poison Creek Formation at the type section south of the WSRP. In addition, new ages from the northern Weiser Cove and Holland Gulch quadrangles east of Weiser indicate the likely presence of Poison Creek Formation in this area (samples 21DF744, 19DF691, 19MB002, and 21DF744; Fig. 6 and Table 1). Although four samples only yield minimum depositional ages (in the 9.9 to 10.7 Ma range), sample 21DF759 provided a depositional age of 10.051 ± 0.007 Ma (Table 1). All are consistent with the Poison Creek Formation assignment. Thickness is uncertain due to erosion at the top of the formation, but likely on the order of ~800–1,800 ft (~250–550 m).

The Chalk Hills Formation east of Payette consists of unconsolidated to moderately consolidated tuffaceous siltstone, tuffaceous claystone, very coarse to fine sandstone, and white to red arkosic fine conglomerate interspersed with ash and tuffaceous pyroclastic intervals (Fig. 7). The formation is composed of massive 40–200 ft (12–60 m) bedsets with "chalky" tuffaceous clay-rich intervals and more isolated iron-stained sandstone beds. A pumice-rich interval in the Chalk Hills Formation from Sulphur Gulch in the Hog Cove Butte quadrangle (Love et al., 2023; Figs. 3 and 7) was dated as part of this work. The interval is a light-gray, non-welded to weakly welded tuff with conspicuous pumice clasts 2–4 in (5–10 cm) in diameter. The pumice contains euhedral 0.02–0.12 in (0.5–3 mm) sanidine and quartz phenocrysts, and zircon grains with a U–Pb age of 7.776 ± 0.013 Ma (sample 16RLB014; Fig. 6 and Table 1). The Chalk Hills Formation is lighter in color and more massive than the underlying Payette and Poison Creek Formations. Exposed soils overlying the Chalk Hills Formation locally have lower clay content than the Payette Formation, resulting in limited desiccation cracks in soils. Dips of the Chalk Hills Formation are less steep than the underlying strata. The top of the formation is poorly defined, but lies above the uppermost thick interval of tuffaceous mudstone. The maximum thickness is estimated to be 4,200 ft (1,280 m), but in places such as Haw Creek and east of Emmett, the Chalk Hills Formation is thin or missing, and the Glenns Ferry Formation rests on the Poison Creek Formation. Near Homedale, Idaho, Malde and Powers (1962) also reported the Chalk Hills Formation to be missing.

The Glenns Ferry Formation north of the WSRP consists of unconsolidated to moderately consolidated siltstone, claystone, very coarse to fine arkosic sandstone, and fine conglomerate interspersed with minor amounts of admixed fine tuffaceous material (Fig. 8). Finer material is a well-bedded finely laminated siltstone to claystone with local diatoms. Arkosic deposits consist of medium gray to tan, fine to coarse, subangular to subrounded grains of quartz, potassium feldspar, plagioclase feldspar, biotite, and muscovite. Minor volcanic lithic fragments consist of brown glass, basalt, and possibly rhyolite. North of the WSRP, the maximum thickness may be as much as 500 ft (150 m).

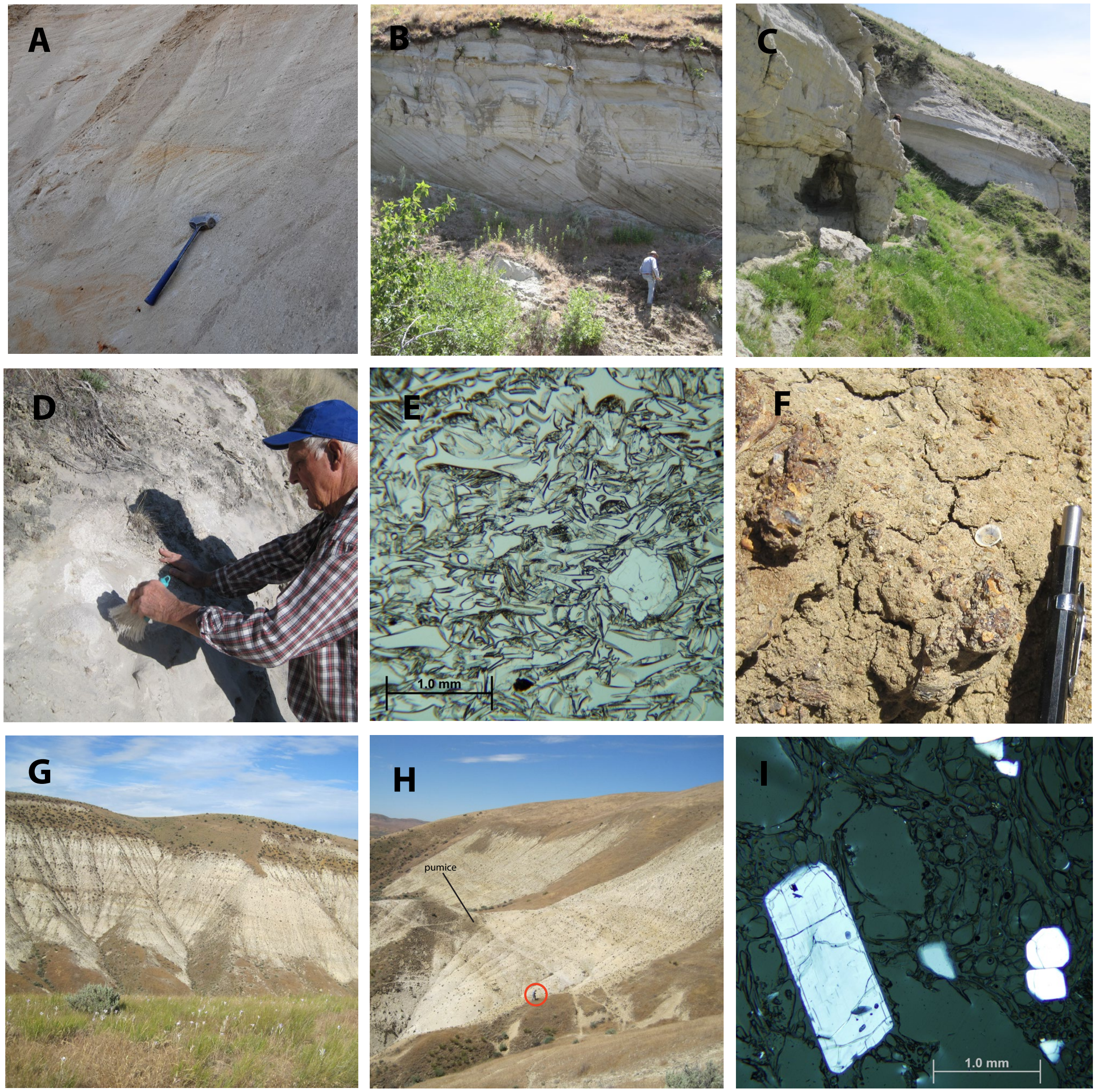


Figure 7. Photographs of field outcrops, thin sections, and hand samples for the Poison Creek Formation (**A–E**) and Chalk Hills Formation (**F–I**). **A,** Rhyolite and sand clasts in the Poison Creek Formation in Poison Creek, south of the western Snake River Plain (WSRP); scale is in mm. **B,** 'Gilbert-type delta' in the Poison Creek Formation in upper Big Willow Creek, Hog Cove Butte quadrangle. **C,** Ash east of Emmett in the upper Poison Creek Formation dated at 9.04 Ma (sample 15RL014). **D,** Pumice-rich outcrop of upper Poison Creek Formation at the Haw Creek locality dated at 9.01 Ma (15RL015a). **E,** Ash in the upper Poison Creek Formation from the central Hog Cove Butte quadrangle with a chemical match to an ash east of Emmett dated at 9.04 Ma (15RL014). **F,** Fish fossils in the upper Chalk Hills, Bannister Basin. **G,** Tuffaceous mudstone underlying oxidized sand that represents the Glenns Ferry/Chalk Hills Formation contact in the Bannister Basin, Hog Cove Butte quadrangle. **H,** Pumice from Sulphur Gulch (16RLB014), Hog Cove Butte quadrangle, dated at 7.78 Ma; S. H. Wood circled for scale. **I,** Photomicrograph of the pumice in photo H.

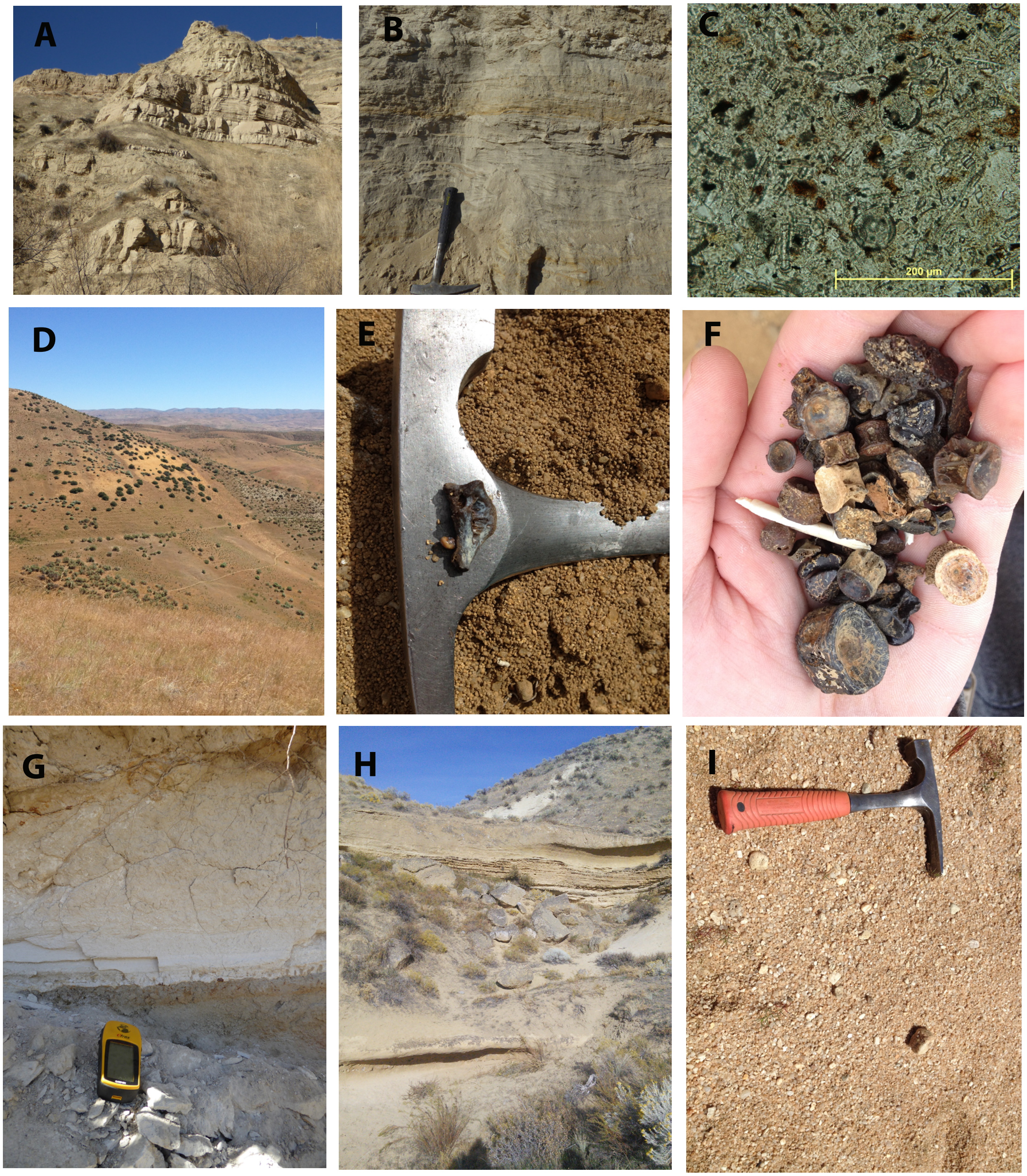


Figure 8. Photographs of field outcrops, thin sections, and hand samples for the Glenns Ferry Formation. **A,** Outcrop in southeast Birding Island quadrangle. **B,** Roadcut along lower Big Willow Creek in Birding Island quadrangle. **C,** Diatoms in the cuttings from Espino 1-2 well at 440 ft (135 m) MD. **D,** Orange sand containing fish fossils in the northern Sheep Ridge quadrangle. **E,** Close-up of the ooids with fish fossils in the southeast part of Hog Cove Butte quadrangle. **F,** Fish fossils in the southeast part of Hog Cove Butte quadrangle. **G**, Ash bed in the southern Sheep Ridge quadrangle. **H,** Lithified oolite beds 12 km northeast of Weiser. **I,** Close-up of sand with fish fossils in the northern Sheep Ridge quadrangle.

Table 2. Scientific or family names in addition to common names for plant macro- and microfossils in the Payette/Emmett area of southwest Idaho. Where possible, common names are based on usage in the USDA Plants Database.

Genus Name **or Family Name**	**Common Name or Family**
Abies	fir
Acer	maple
Alnus	alder
Amaranthaceae	amaranth
Artemisia	mugwort, wormwood, sagebrush
Asteraceae/Compositae	aster, daisy, composite, sunflower family
Berberis	barberry
Betula	birch
Carpinus	hornbeam
Carya	hickory
Caryophyllaceae	carnation
Castanea	chestnut
Cathaya	pine family, Pinaceae
Cedrela	mahogany family, Melaceae
Cedrus	cedar
Celtis	hackberry, nettletree
Cercidiphyllum	katsura tree
Chamaecyparis	false cypress
Chenopodiaceae	saltbrush
Cornus	dogwood
Elaeagnus	silverberry
Ephedra	mormon tea
Equisetum	horsetail, scouringrush
Ericaceae	heather
Fabaceae	legume, pea, bean family
Fagaceae	beech family
Fagus	beech
Fraxinus	olive and lilac
Ginkgo	ginkgo
Glyptostrobus	Chinese water pine
Humulus	hop
Ilex	holly
Isoetes	quillwort
Juglans	walnut
Juniperus	juniper

Genus Name **or Family Name**	**Common Name or Family**
Larix	larch
Lauraceae	Laurel family
Liquidambar	sweetgum
Lithocarpus	stone oak
Metasequoia	dawn redwood
Myrica	bayberry, wax myrtle
Myriophyllum	watermilfoil family, Haloragaceae
Nymphaea	waterlily
Nyssa	tupelo
Onagraceae	evening primose family
Opuntioideae	cactaceae family
Ostrya	hop-hornbeam
Picea	spruce
Pinus	pine
Platanus	sycamore
Poaceae/Gramineae	grass family
Podocarpus	podocarp family
Pseudotsuga	Douglas fir
Pterocarya	wingnut
Quercus	oak
Rhus	sumac
Rosaceae	rose family
Salix	willow
Sarcobatus	greasewood
Sassafras	sassafras
Saxifragaceae	saxifrage family
Sequoia	redwood
Tamarix	Athel tamarisk
Taxodium Cupressaceae	bald cypress, juniper
Taxus	yew
Tilia	basswood/linden
Tsuga	hemlock
Ulmus/Zelkova	elm and zelkova
Veronica	common gypsyweed

The Glenns Ferry Formation differs from the underlying Chalk Hills Formation in that it contains less ash and less mudstone, contains less clay overall, and is darker (brown to tan) and more clearly layered when viewed from a distance (or in Google Earth images where the unit typically has a distinct maroon color). Stratigraphic architecture and appearance are tan thinly bedded sequences with local thicker 5–50 ft (1.5–15 m) sandstone beds. Mud-cracked surface soils are rare.

Biostratigraphy

More than 50 distinct palynomorphs were identified (Table 2) from surface samples. Palynomorph biozones are defined using fossil assemblages as well as index fossil grains. Surface samples of nearby outcrops that have been radiometrically dated were instrumental in providing time constraints for the floral assemblages that define each of the formations. Plant macrofossils from surface outcrops were also described, and are compared here to determine vegetation type in each formation. Results are given in Table 3, and select grains are shown graphically and in photographs in Figs. 9A–C.

Palynomorphs from 13 surface localities (Table 3) indicate that during the deposition of the Payette Formation, common conifers in the forests included *Abies, Picea, Taxus, Pinus, Tsuga, Pseudotsuga/Larix*, *Cedrus,* and *Taxodium*/Cupressaceae (see Table 2 for common names). Deciduous trees and shrubs included *Acer, Alnus, Betula, Carya, Castanea, Elaeagnus, Liquidambar, Ostrya, Platanus, Pterocarya, Juglans, Quercus, Tilia, Nyssa*, and *Ulmus/Zelkova*. Herbaceous and other small plants included Caryophyllaceae and *Isoetes*. Less common grains included Chenopodiaceae/Amaranthaceae, *Fagus*, *Fraxinus*, Poaceae/Gramineae, *Nymphaea*, Ericaceae, and *Salix*.

Three surface localities also contained plant macrofossils (leaves, reproductive structures, and branches) in the Payette Formation (Fig. 3, Table 3). Identified leaves and needles are from *Metasequoia, Cercidophyllum, Glyptostrobus, Chamaecyparis,* Lauraceae, *Platanus, Taxodium, Sassafras, Lithocarpus, Quercus, Sequoia, Equisetum,* and possibly *Castanea* and *Betula.*

Table 3. Palynomorph and macrofossils in the Payette/Emmett area of southwest Idaho. Surface palynomorph samples and macrofossils are shown in upper part of the table. Note palynomorphs that are described for specific U–Pb ages. Lower part of the table contains identified palynomorphs in each of the subsurface wells. The presence of a palynomorph grain is indicated by a "P." The presence of plant macrofossils are indicated by an "M". Designations: Chalk Hills = Chalk Hills Formation; Poison Creek = Poison Creek Formation; Payette = Payette Formation; Glenns Ferry = Glenns Ferry Formation. Genus names are listed in *italics*, e.g., *Abie*s, whereas family names are listed in normal type, e.g., Asteraceae.

Map Desig	Map Sym.	Location notes	Sample #	*Abies*	*Acer*	*Alnus*	*Artemisia*	Asteraceae/Compositae	*Betula*	*Carpinus*	*Carya*	Caryophyllaceae	*Castanea*	*Cathaya*	*Cedrus*	*Cercidophyllum (M)*	*Chamaecyparis (M)*	Chenopodiaceae	*Elaeagnus*	*Ephedra*	Equisetum (M)	Ericaceae	*Fagus*	*Fraxinus*	*Glyptostrobus (M)*	*Humulus*	*Ilex*
Chalk Hills	xx3	Sulfur Gulch Pumice #1 (near 7.78 Ma)	16RLB019	P		P			P									P									
Chalk Hills	xx4	Bannister Pumice #2 (near 7.78 Ma)	16RLB026A	P	P	P					P		P	P				P				P					
Poison Creek	xx1	Haw Creek Roadcut (near 9.0057 Ma)	15RLB017																								
Poison Creek	xx2	South of Train Tunnel, NE Emmett	15RLB022			P						P						P									
Poison Creek	xx5	NE Emmett Fossil Site	17RL252			P												P									
Payette	xx6	Indian Creek (near 16.394 Ma)	15RLB010			P			P		P												P			P	
Payette	xx6	Indian Creek (near 16.394 Ma)	15RLB011																								
Payette	xx7	NW on map, Hog Cove Butte	16RLB009																								
Payette	xx8	NW on map, Hog Cove Butte	16RLB010						P		P							P			M						
Payette	xx9	NW on map, Hog Cove Butte	16RLB012A		P	P					P		P														
Payette	xx9	NW on map, Hog Cove Butte	16RLB012B	P		P			P																		
Payette	xx10	Equisetum Site, Paddock Valley	15RLB027	P														P			M				M		
Payette?	xx11	Metasequoia/Cercidophyllum Site	15RLB030						M							M		P					M		M		
Payette	xx12	Patricks Great Fossil Leaf Locality	15RLB031	P	P	P			P, M		P		P, M			M	M	P			M	P	P	P	M		
Chalk Hills	12	Island Capital 1-19, Willow Field	320					P							P			P					P				
Poison Creek	12	Island Capital 1-19, Willow Field	1670	P	P	P	P				P	P											P	P			
Poison Creek	12	Island Capital 1-19, Willow Field	1950	P	P	P		P			P								P								
Poison Creek	12	Island Capital 1-19, Willow Field	2590			P					P	P	P					P									
Payette	12	Island Capital 1-19, Willow Field	3520	P		P					P							P	P								
Payette	12	Island Capital 1-19, Willow Field	4050	P	P	P																	P				
Chalk Hills	13	Schwarz 1-10, Hog Cove Butte	130	P				P			P	P						P	P								
Poison Creek	13	Schwarz 1-10, Hog Cove Butte	870	P		P	P	P	P		P	P	P		P			P		P				P			
Poison Creek	13	Schwarz 1-10, Hog Cove Butte	1330	P	P	P			P		P		P									P	P				
Payette	13	Schwarz 1-10, Hog Cove Butte	1540	P	P	P					P							P					P				
Payette	13	Schwarz 1-10, Hog Cove Butte	2060		P	P	P	P	P	P	P	P	P		P				P	P			P	P			
Glenns Ferry	25	State 1-17, Hamilton Field	630		P	P	P	P				P							P	P							
Chalk Hills	25	State 1-17, Hamilton Field	1350				P	P	P						P			P									
Poison Creek	25	State 1-17, Hamilton Field	3600	P	P			P				P		P				P									
Payette	25	State 1-17, Hamilton Field	4230	P	P																						P
Glenns Ferry	21	Espino 1-2, Hamilton Field	830			P			P	P								P	P	P			P				
Chalk Hills	21	Espino 1-2, Hamilton Field	1160	P				P		P								P									
Chalk Hills	21	Espino 1-2, Hamilton Field	1640	P	P	P		P		P	P								P								
Poison Creek	21	Espino 1-2, Hamilton Field	3170			P					P																
Poison Creek	21	Espino 1-2, Hamilton Field	3850	P				P	P										P								
Chalk Hills?	4	ML Investments 1-10, Willow Field	330	P			P	P	P	P								P	P				P				
Chalk Hills	4	ML Investments 1-10, Willow Field	1330			P	P	P										P					P				
Chalk Hills	4	ML Investments 1-10, Willow Field	1940	P							P		P														
Chalk Hills	4	ML Investments 1-10, Willow Field	2810	P			P	P						P													
Chalk Hills?	4	ML Investments 1-10, Willow Field	3880	P								P															
Poison Creek?	4	ML Investments 1-10, Willow Field	4900	P																				P			

Map Desig	Map Sym.	Location notes	Sample #	*Isoetes*	*Juglans*	*Juniperus*	Lauraceae (M)	*Liquidambar*	*Lithocarpus (M)*	*Metasequoia (M)*	monolete spore	*Nymphaea*	*Nyssa*	Onagraceae	*Ostrya*	*Picea*	*Pinus*	*Platanus*	Poaceae/Gramineae	*Podocarpus*	*Pseudotsuga/Larix*	*Pterocarya*	*Quercus*	*Rhus*	Rosaceae	*Salix*	*Sarcobatus*	*Sassafras (M)*	*Sequoia (M)*	*Taxodium (M)*	*Taxus*	TCT	*Tilia*	trilete spore	*Tsuga*	*Ulmus/Zelkova*
Chalk Hills	xx3	Sulfur Gulch Pumice #1 (near 7.78 Ma)	16RLB019		P										P	P	P					P										P	P			
Chalk Hills	xx4	Bannister Pumice #2 (near 7.78 Ma)	16RLB026A										P			P	P	P			P	P	P									P				
Poison Creek	xx1	Haw Creek Roadcut (near 9.0057 Ma)	15RLB017		M																P		M									P				
Poison Creek	xx2	South of Train Tunnel, NE Emmett	15RLB022																			P										P				P
Poison Creek	xx5	NE Emmett Fossil Site	17RL252																			P										P				
Payette	xx6	Indian Creek (near 16.394 Ma)	15RLB010		P			P				P				P					P			P							P	P			P	P
Payette	xx6	Indian Creek (near 16.394 Ma)	15RLB011																		P											P				
Payette	xx7	NW on map, Hog Cove Butte	16RLB009		P												P					P										P				
Payette	xx8	NW on map, Hog Cove Butte	16RLB010					P								P						P										P	P			P
Payette	xx9	NW on map, Hog Cove Butte	16RLB012A		P											P	P					P										P				P
Payette	xx9	NW on map, Hog Cove Butte	16RLB012B		P											P	P				P	P										P			P	P
Payette	xx10	Equisetum Site, Paddock Valley	15RLB027															P, M			P	P						M			P	P				P
Payette?	xx11	Metasequoia/Cercidophyllum Site	15RLB030							M						P	P	P					P									P				
Payette	xx12	Patricks Great Fossil Leaf Locality	15RLB031		P		M	P	M	M			P		P	P	P	P, M				P	P, M			P		M	M	M	P	P	P		P	
Chalk Hills	12	Island Capital 1-19, Willow Field	320		P											P	P					P	P												P	
Poison Creek	12	Island Capital 1-19, Willow Field	1670		P			P				P	P			P	P	P	P		P	P	P			P					P	P				P
Poison Creek	12	Island Capital 1-19, Willow Field	1950	P	P			P			P		P		P	P	P	P		P		P	P											P		P
Poison Creek	12	Island Capital 1-19, Willow Field	2590												P	P	P				P	P										P			P	P
Payette	12	Island Capital 1-19, Willow Field	3520		P			P			P					P	P					P									P	P	P			P
Payette	12	Island Capital 1-19, Willow Field	4050		P			P							P	P		P				P	P									P				P
Chalk Hills	13	Schwarz 1-10, Hog Cove Butte	130		P	P										P	P		P		P		P													
Poison Creek	13	Schwarz 1-10, Hog Cove Butte	870		P						P			P				P	P		P	P			P		P				P	P		P	P	P
Poison Creek	13	Schwarz 1-10, Hog Cove Butte	1330		P						P				P	P	P				P	P	P			P								P	P	
Payette	13	Schwarz 1-10, Hog Cove Butte	1540												P		P					P											P			P
Payette	13	Schwarz 1-10, Hog Cove Butte	2060		P			P			P	P			P	P	P	P			P	P	P			P					P		P		P	P
Glenns Ferry	25	State 1-17, Hamilton Field	630		P							P	P			P	P	P		P			P		P	P	P					P				
Chalk Hills	25	State 1-17, Hamilton Field	1350													P	P	P			P											P		P		
Poison Creek	25	State 1-17, Hamilton Field	3600					P										P		P			P									P				
Payette	25	State 1-17, Hamilton Field	4230		P			P								P		P				P					P									
Glenns Ferry	21	Espino 1-2, Hamilton Field	830		P							P				P	P		P				P									P				P
Chalk Hills	21	Espino 1-2, Hamilton Field	1160		P							P				P	P		P				P													P
Chalk Hills	21	Espino 1-2, Hamilton Field	1640		P											P	P	P	P			P	P													P
Poison Creek	21	Espino 1-2, Hamilton Field	3170		P			P								P		P				P					P				P	P				P
Poison Creek	21	Espino 1-2, Hamilton Field	3850		P						P					P	P	P			P	P				P	P					P				P
Chalk Hills?	4	ML Investments 1-10, Willow Field	330		P								P			P	P		P				P			P						P	P			
Chalk Hills	4	ML Investments 1-10, Willow Field	1330		P							P				P	P						P			P	P					P			P	
Chalk Hills	4	ML Investments 1-10, Willow Field	1940													P	P					P	P			P						P				
Chalk Hills	4	ML Investments 1-10, Willow Field	2810		P						P					P	P	P								P	P									P
Chalk Hills?	4	ML Investments 1-10, Willow Field	3880	P	P			P				P				P	P	P				P										P				
Poison Creek?	4	ML Investments 1-10, Willow Field	4900													P	P															P				P

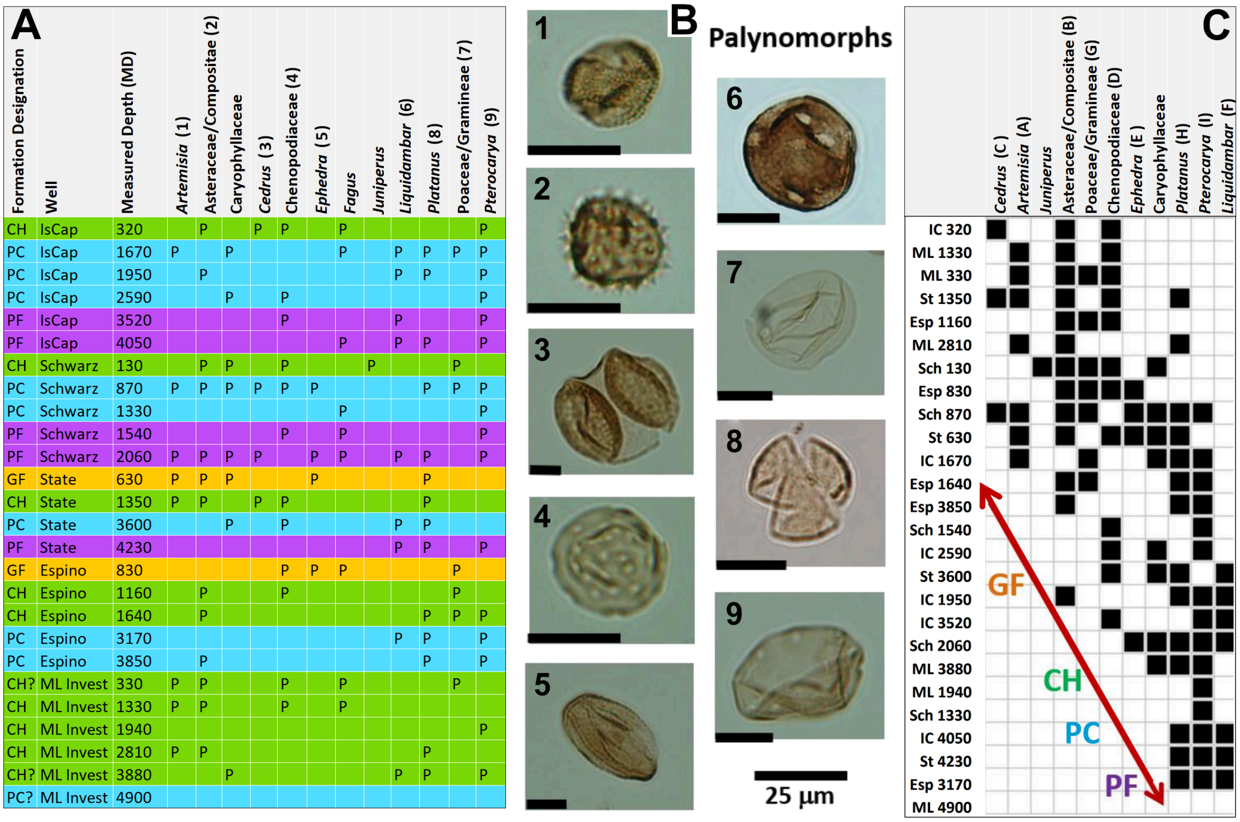


Figure 9. A, Index pollen grains plotted against subsurface well depth (well locations in Fig. 3). CH = Chalk Hills Formation; PC = Poison Creek Formation, PF = Payette Formation, GF = Glenns Ferry Formation; IsCap = Island Capital; ML = ML Investments. **B,** Selected pollen photographs show grains that were important for formation designations. These include: (1) Artemesia; (2) Asteraceae; (3) Cedrus; (4) Chenopodiaceae; (5) Ephedra; (6) Liquidambar; (7) Poaceae/Graminea; (8) Platanus; and (9) Pterocarya. **C,** Seriation plot (presence vs. absence diagram) that shows common index grains to the Glenns Ferry (GF), Chalk Hills (CH), Poison Creek (PC), and Payette (PF) Formations, and how those grains change with depth (i.e., age).

In the mapping area, a lignite bed occurs along Indian Creek (sample xx6, Fig. 3), and records macroflora of *Metasequoia* and possible *Quercus*, as well as small pieces of wood. Interspersed with sedimentary interbeds, this section contains ~5 ft (~1.5 m) of coal and other organic-rich rock. Nearby dating indicates that this lignite would be slightly older than the ~16.4 Ma rhyolite dated nearby (sample 16DF438 collected ~700 ft (210 m) stratigraphically above sample xx6; Fig. 3 and Table 1).

Organic material is also reported in two of the oil and gas well logs in strata that we assign to the Payette Formation. In well DJS Properties 1-14 (Fig. 3), organic material is in the subsurface at depths of 4,920–5,020 ft (1,500–1,530 m), and again from 5,900–5,940 ft (1,800–1,810 m). These organic-rich beds are interbedded dark-gray to black shale with thin coaly intervals. Well DJS Properties 1-15 also contains dark gray to black coaly intervals that are interbedded with claystone from 3,840–3,970 ft (1,170–1,210 m).

The palynomorph assemblages from the Poison Creek and Chalk Hills Formations included similar genera as the Payette Formation with the addition of *Cathaya*, *Ephedra*, *Sarcobatus*, Rosaceae, and Onagraceae. More abundant *Pinus, Cedrus,* Caryophyllaceae, Asteraceae, *Artemisia,* and Chenopodiaceae also occur, whereas *Liquidambar* disappeared. Palynomorph samples xx1, xx3, and xx4 show assemblages characteristic of the Poison Creek and Chalk Hills Formations. Sample xx1 was collected about 330 ft (100 m) below a 9.005 ± 0.015 Ma pumice bed (15RL015a). Sample xx3 was collected about 80 ft (25 m) above the 7.776 ± 0.013 Ma Sulphur Gulch pumice bed (16RLB014). Sample xx4 was collected adjacent to a

Figure 10. Collection intervals and formation designations based on palynomorphs extracted from well cuttings. Green = Chalk Hills Formation; purple = Payette Formation; orange = Glenns Ferry Formation; blue = Poison Creek Formation. Other abbreviations: Cut Log = drafted from well cutting samples taken at 10-foot intervals; MD = measured depth, in ft; GR Cali = gamma ray calibration; DENS = density; DPHI = density-porosity; NPHI = neutron-porosity; GR = gamma ray.

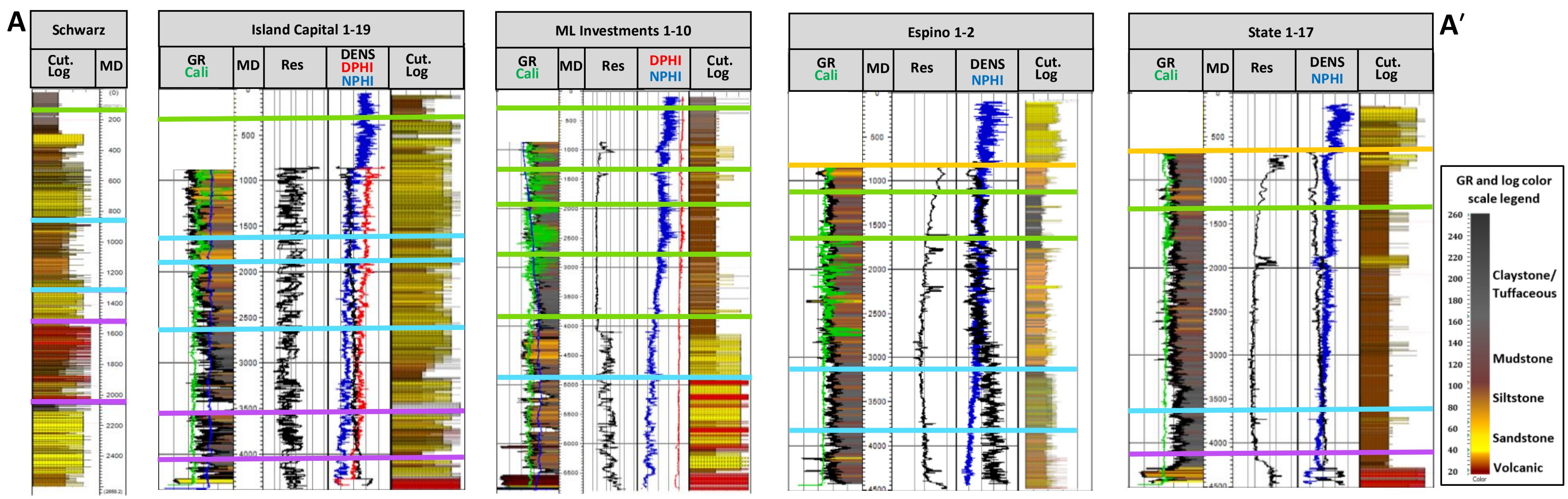
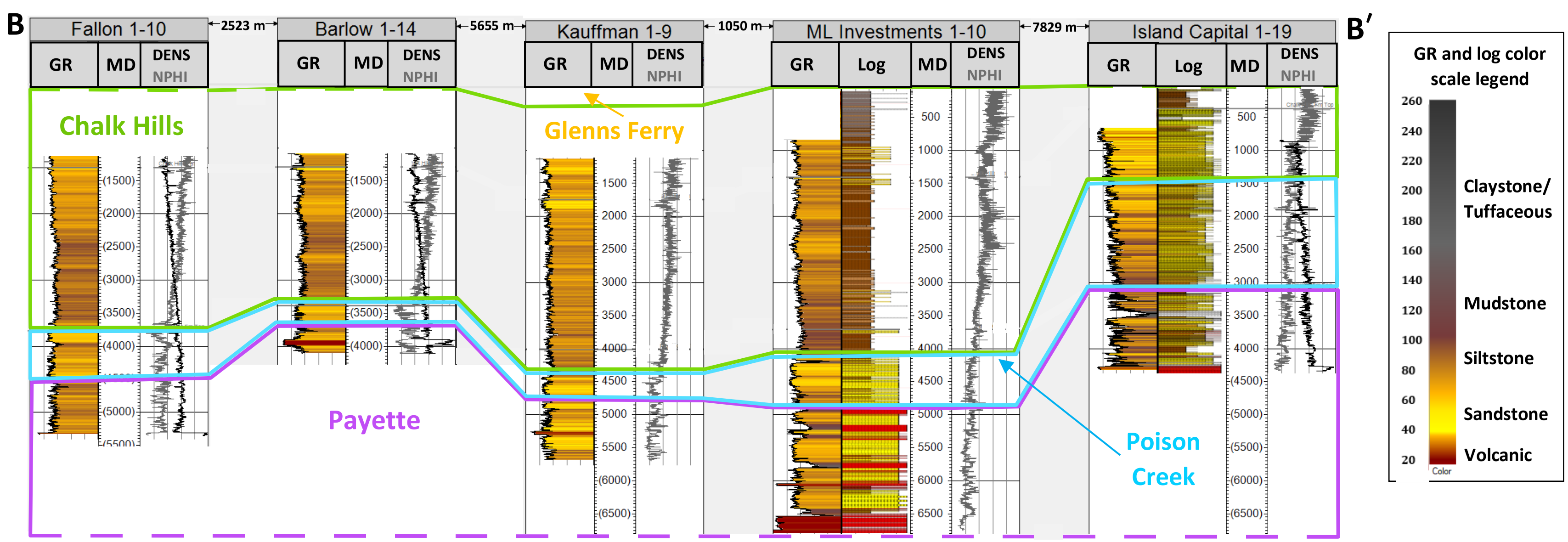


Figure 11. Well top mapping based on stratigraphic packages and new palynology data. Locations of wells are shown in Figure 3. Scales for logs (from left to right) are: gamma ray (GR) 0–260 gAPI; density (DENS) 1.3–2.95 g/cm^3; neutron-porosity (NPHI) 0.0085–800. Log = drafted from well cutting samples taken at 10-foot intervals. MD = measured depth (in ft).



pumice locality whose chemistry matches the Sulphur Gulch pumice.

During deposition of the Glenns Ferry Formation, an increase of Asteraceae, *Juniperus*, Poaceae/Gramineae, *Artemisia*, Chenopodiaceae, Asteraceae, and *Sarcobatus* appeared. *Pterocarya* is absent, whereas it was in high abundance during the Chalk Hills depositional time. The index palynomorph grains represent the change in vegetation, and therefore climate. The biostratigraphically important grains throughout the entire sedimentary section are: *Juniperus,* Poaceae/Gramineae*, Artemisia,* Asteraceae*, Pterocarya,* and *Liquidambar* (Table 3).

Surficial biostratigraphy coupled with absolute U–Pb ages aided in the subsurface correlation of well logs using palynomorphs (Fig. 10). Two intervals in Island Capital 1-19, at 3,520 and 4,050 ft (1,073 and 1,234 m), contain the biostratigraphically useful index fossil grain *Liquidambar*, which disappeared from the fossil record soon after the mid-Miocene climatic optimum (W. Rember, personal communication, 2018). Many of the grassy, herbaceous desert steppe flora of the late Miocene and early Pliocene are absent in the lower depths (Table 3).

Liquidambar occurs along with a diverse assemblage that indicates a mixture of deciduous and coniferous forests from 1,670 to 2,070 ft (509–631 m) in Schwarz 1-10. Although *Liquidambar* does not occur between the depths of 1,330 and 1,550 ft (405–472 m), we are designating this interval as Poison Creek Formation due to nearby surface mapping (Love et al., 2023). At the depth of 870–880 ft (265–268 m) in Schwarz 1-10, typical Chalk Hills flora occur with fewer deciduous trees, and the drier desert-steppe plants are more abundant. We designate the bottommost zone of ML Investments 1-10 at 4,900 ft (1,494 m) as Payette Formation. *Liquidambar* is present at 3,880 ft (1,183 m) as well. This occurrence does not match the coarse lithology (sandstone) that we have mapped in the Poison Creek Formation. Perhaps it is a reworked grain in the Chalk Hills Formation. Typical Chalk Hills palynoflora occur at the depth of 1,320–2,790 ft (402–850 m). Samples at 330 ft (100 m) have typical Glenns Ferry Formation grains.

Cuttings from two wells in the Hamilton field to the south (Espino 1-2 and State 1-17; Fig. 3) were also examined. The bottom two intervals in Espino 1-2—3,850 and 3,170 ft (1,173 and 966 m)—are here designated as Poison Creek Formation based on lithology and well-preserved *Liquidambar* pollen grains in the 3,170 ft (966 m) interval. Interval 4,230–4,240 ft (1,289–1,292 m) in State 1-17 contained a single degraded *Liquidambar* grain, and the depth of 3,600–3,610 ft (1,097–1,100 m) contained a well-preserved *Liquidambar* grain, placing the intervals in the time period of the mid-Miocene climatic optimum. Intervals between 1,148 and 1,640 ft (350–500 m) in Espino 1-2 and 1,350–1,360 ft (411–414 m) in State 1-17 are designated as Chalk Hills Formation. The uppermost intervals sampled at 830 ft (253 m) in Espino 1-2 and 620 ft (189 m) in State 1-17 are interpreted as being deposited during Glenns Ferry time. There are differences in palynomorphs between these intervals, but both contain copious grassland-desert sagebrush steppe flora. Two notable grains that are absent to rare are *Pterocarya* and *Platanus*. Both of these grains are common in the lower formations, and become much less common in the Glenns Ferry flora.

Using the above palynomorph analysis, and the stratigraphic architecture and rock types interpreted from the gamma ray and resistivity petrophysical logs, formation tops are extrapolated from the wells with biostratigraphic control to other wells in the Willow and Hamilton fields without biostratigraphic control (Fig. 11). Fining upward, coarsening upward, and aggradational packages were utilized in well log correlation. Also, flooding surfaces and maximum flooding surfaces provided chronostratigraphic markers. Here, horizons are correlated across the fields. Using those correlations, estimated locations of each of the formation tops are indicated at depth.

DISCUSSION

Payette Formation

Originally the Payette Formation was thought to be deposited mostly in a large lacustrine setting (Lindgren, 1898; Buwalda, 1924). Based on the uncertainty of the assignment of the Payette Formation and overlying Idaho Group sedimentary packages, it appears that this designation was a result of some of the Lake Idaho sediments being included within the Payette Formation (Kirkham, 1931). Lindgren's (1898) comment in a footnote (p. 632) "to separate the deposits of the two formations is not always easy" with which we heartily agree, but an approximate contact is now recognized by our mapping and dating efforts near and northwest of Emmett. We interpret the dominant depositional environment for the Payette Formation in the study area to be fluvial-deltaic and localized quiet-water back swamps, with lesser lacustrine deposits. The fluvial-deltaic deposits are characterized by coarse to very coarse arkose to quartz arenite to fine conglomerate. Finer lacustrine intervals are thick- to thin-bedded tuffaceous mudstone and volcanic ash deposits. These locally contain sparse thin beds containing fossil-bearing ostracod and plant remains, which act as distinct local marker beds (Breedlovestrout et al., 2017). The brown and reddish mudstones are interpreted as paleosols due to their high clay content and local occurrence of rootlets, and are indicative of the warmer paleoclimate of the mid-

Miocene climatic optimum. The Payette Formation north of Boise near Horseshoe Bend (HSB in Fig. 1) contains carbonaceous shale and coal. The coal occurs as thin beds up to 3 ft (~1 m) thick, and is subbituminous and lignitic in maturity (Bowen, 1913).

Our 15.882 ± 0.020 Ma U/Pb zircon age on the locally prominent welded lapilli tuff bed with the Payette Formation is similar to the ~16.0–15.8 Ma tuff of Leslie Gulch and related volcanic rocks of the Rooster Comb caldera (Streck et al., 2015; Benson and Mahood, 2017; Black, 2021) 55 miles (90 km) southwest of this Payette Formation welded tuff occurrence. Whereas the age correlation is the same, the tuff of Leslie Gulch is a rhyolite (75.8% SiO_2) with sodic sanidine phenocrysts and no plagioclase (Benson and Mahood 2016). In contrast, the Payette welded tuff is a dacite (70.9% SiO_2) with a small percentage of plagioclase phenocrysts. The Birch Creek low-silica rhyolite lavas that occur south of the Rooster Comb caldera are plagioclase-bearing, and although only minor tuffs are identified, Benson and Mahood (2016) allow that they could be earlier or contemporaneous with the tuff of Leslie Gulch. Thus, the dacitic Payette welded tuff could be from an unrecognized tuff eruption of the Birch Creek magma type.

The tuff of Leslie Gulch was emplaced on an eroded surface of Succor Creek Formation, and sedimentation of the formation continued after emplacement of the tuff (Benson and Mahood, 2016). Downing (1992) measured more than 650 ft (200 m) of fluvial-lacustrine sediment of the upper Succor Creek Formation that contains mammal fossils and the widespread "Obliterator ash" with an originally reported $^{40}Ar/^{39}Ar$ sanidine age of 14.93 ± 0.08 Ma (Downing and Swisher, 1993) recalculated to 15.02 ± 0.08 Ma by Streck et al. (2015). The Obliterator ash is identified by geochemical correlation in the Payette Formation in the Holland Gulch quadrangle (Forester and Wood, 2012; Nash and Perkins, 2012), and now mapped as a prominent ash bed in the Alkali Creek and Dry Creek drainages of the Hog Cove Butte quadrangle, where it commonly contains ostracods (Love et al., 2023). At the Alkali Creek locality, the ash lies ~330 ft (~100 m) above the 15.91 Ma welded tuff. These ages and correlations indicate the sedimentary strata we assign to the Payette Formation were deposited prior to the 16.39 Ma Indian Creek rhyolite and continued to an unknown amount of time after 15.0 Ma Obliterator ash. Thus, the earlier definition of the Payette Formation that only includes sediments interbedded within the CRBG volcanic flows by Kirkham (1931) needs to be revised.

The plant macrofossil locality south of Paddock Valley Reservoir in the Payette Formation is one of the few sites where *Sequoia* and *Metasequoia* overlap in the fossil record (P. Fields, personal communication, 2019). Although some of these genera do not have readily preserved palynomorphs, this assemblage aligns with the pollen grain assemblages at nearby sites of similar age. The Payette Formation is the primary sedimentary formation with observed lignitic and subbituminous coal interbeds and, as noted above, is likely the main hydrocarbon source in the basin. The mid-Miocene climatic optimum provided a warm environment conducive to abundant, diverse plant growth and high rates of plant death and accumulation.

The Mascall Formation of central Oregon was deposited during a similar time to the Payette Formation (~17 to 12 Ma; Bestland et al., 2008; McClaughry et al., 2021). Dillhoff et al., (2009) and Chaney and Axelrod (1959) reported 15 common species that occur in the Mascall Formation; these include different species of *Taxodium, Quercus, Carya, Platanus, Acer, Metasequoia, Ginkgo, Ulmus, Cedrela,* and *Betula*. Extensive work has also been done on the age-equivalent Latah Formation of eastern Washington and northern Idaho. Although Poaceae/Gramineae*, Elaeagnus,* and *Isoetes* grains are infrequent, the other palynomorphs mentioned above are common (Knowlton, 1926; Smiley et al., 1975). The genera in both the Latah and Mascall Formations discussed above were common during the mid-Miocene, and have commonalities to the Payette Formation flora and the palynomorphs analyzed. Similar modern forests that contain these genera are from eastern Asia and eastern North America (Dillhoff et al., 2009). Cypress swamps today occur in the Mississippi Valley near the Gulf of Mexico. Other less diagnostic grains not mentioned here are included in Table 3. These results also help establish the lower age of the Payette Formation at about 17 to 16 Ma during the mid-Miocene climatic optimum based on the presence of *Liquidambar*. The minimum age for the Payette is less than 15.0 Ma based upon the occurrence of the Obliterator ash exposed in Alkali Creek. Petroleum wells to the west suggest approximately 1,000 ft (300 m) of undated section may occur above this ash, although the Obliterator ash has not been identified in wells.

Fields (1983) examined macroflora in some of the organic-rich layers from the type section of the Payette Formation near Horseshoe Bend, and documented dominantly *Populus, Quercus, Salix*, and *Taxodium*. Other less common paleoflora are *Pinus, Picea, Abies, Pseudotsuga, Acer, Fagus*, and *Thuja*. Shah (1966, 1968) also studied macrofossils in the Payette and Poison Creek Formations near Weiser, and identified these common paleofloras. These floras document a temperate, broadleaved forest ecosystem and reconstruct a paleoclimate of southern Idaho that was 3 to 4°C warmer during the mid-Miocene climatic optimum compared to today (Leopold and Denton, 1987; You et al., 2009; Mustoe and Leopold, 2014; Sosbian et al., 2020).

The results of our new geochronology, mapping, and biostratigraphy indicate that the Payette Formation is interbedded with, but also locally overlies the middle Miocene CRBG and Weiser volcanic field (WVF) (Figs. 2, 3, and 4). As discussed previously, there have been different definitions of the Payette Formation—whether it is only interbedded with or whether it is interbedded with and overlies the CRBG and WVF (Lindgren, 1898; Kirkham, 1931). We redefine it here as the sedimentary rocks that overlie and are interbedded with the CRBG and WVF, spanning the mid-Miocene climatic optimum. The top is defined by the overlying Poison Creek Formation scour surface and subsequent sand deposition.

Poison Creek Formation

The depositional environment of the Poison Creek Formation is interpreted here as 'Gilbert-type delta' deposits, and laterally correlative facies formed during the initiation of Lake Idaho. The ages determined here for the Poison Creek Formation in the Emmett area range from < 9.9 to 9.0 Ma. East of Weiser, maximum depositional ages from three samples range from 10.7 to 10.0 Ma, and a fourth sample yielded a depositional age of 10.1 Ma. Our mapping near Emmett indicates that the top of the Poison Creek Formation is marked by a thick reddish brown paleosol 33–115 ft (10–35 m) thick developed above a dated 9.041 Ma ash (Feeney et al., 2018). This red tuffaceous paleosol is a distinct marker bed that locally defines the top of the formation north and south of the WSRP (Warner, 1981).

Whereas the Poison Creek Formation was deposited at a time when conifers were present (Cupressaceae, *Pinus*, and *Pseudotsuga*), sagebrush-steppe habitat began to appear in the rock record as soon as 12 Ma (Davis and Ellis, 2010). *Ephedra, Sarcobatus,* Asteraceae, and *Artemisia* represent the onset of drier vegetation and are present in the subsurface palynomorph samples. There is also a distinct disappearance of a key index palynomorph during the Poison Creek and Chalk Hills depositional times. *Liquidambar* disappeared in the mapping area and regionally in similar aged strata after the mid-Miocene climatic optimum (W. Rember, personal communication, 2016).

The nearby Pickett Creek flora of Owyhee County, Idaho, on the south side of the WSRP, are similar in age to the upper section of the Poison Creek Formation. Chemical analyses of two ash samples from Pickett Creek suggest an age of 10.5 to 8.5 Ma (Buechler et al., 2007). Abundant palynomorphs listed for the Pickett Creek flora are *Pinus* and *Quercus*, and grains that also indicate a slightly drier paleoclimate are Asteraceae, Onagraceae, and Chenopodiaceae/Amaranthaceae. The Musselshell Creek flora in northern Idaho is slightly older than the Pickett Creek flora. Ages of the Musselshell Creek flora span 12.5 to 10.5 Ma (Baghai and Jorstad, 1995). In this flora, a similar trend exists: the deciduous hardwood flora common also to the Payette Formation was replaced by drier, more temperate forests; *Taxodium*, *Sequoia*, and *Metasequoia* are replaced by *Abies*, *Picea*, and *Pinus* (Baghai and Jorstad, 1995).

Chalk Hills Formation

The Chalk Hills deposits are interpreted as lacustrine based on the parallel-laminated, fine-grained deposits and the presence of diatoms. A minor fluvial to subaerial channel component is suggested by sands in isolated compartmentalized beds. Regionally, lowermost deposits may represent a shallow disconnected lake with close-to-the source fluvial, deltaic, and volcanic inputs. As time progressed, the lake level apparently rose, resulting in more massive, laterally continuous, highly tuffaceous lacustrine deposits. The Sulphur Gulch pumice interval forms an important marker bed, and is roughly 230 ft (70 m) above the base of the Chalk Hills Formation. Its 7.76 Ma age affirms its correlation to the Chalk Hills Formation on the south side of the Snake River Plain (Kimmel, 1982; Smith et al., 1982; Perkins et al., 1998; Smith and Cossel, 2002).

Viney et al. (2017) documented at least 15 angiosperm and gymnosperm types in the Bruneau Woodpile of the Chalk Hills Formation south of Bruneau (Fig. 1). This site was dated at ca. 6.85 Ma. Macrofossils included gynmosperms Cupressaceae and *Pinus*, and angiosperms included cf. *Berberis,* Fabaceae, *Quercus, Carya, Salix, Acer,* and *Ulmus.* Except for the *Berberis* and Fabaceae, the Bruneau Woodpile macrofossils (Viney et al., 2017) are comparable to the palynomorphs presented here, and represent a subset of the drier forests of the late Miocene. These observations are also supported by work in the central Snake River Plain by Davis and Ellis (2010). There, gymnosperm and angiosperm forests were near sagebrush-steppe vegetation (*Artemisia*, Poaceae, and Chenopodiaceae) in the drier lowlands.

Glenns Ferry Formation

Deposits of the Glenns Ferry Formation are interpreted here as partly lacustrine based on an abundance of parallel laminae and fine grain size found regionally. A fluvial and deltaic component consists of interbedded siltstone to fine to coarse sandstone (Wood and Clemens, 2002). We have no new ages to report from our mapping area.

A general cooling and drying trend continued from the Miocene to the Pliocene in Idaho. More arid, sagebrush-woodland and grassland-steppe environment with smaller herbaceous plants and an increase of Asteraceae characterized the Pliocene–early Pleistocene Glenns Ferry Formation (Leopold and Denton, 1987; Mustoe and Leopold, 2014). The deciduous trees that were regionally still abundant during the late Miocene became rare (*Carya, Quercus, Acer, Juglans*, and *Ulmus*; Mustoe and Leopold, 2014). More frequent *Juniperus*, Poaceae/Gramineae, *Artemisia*, Chenopodiaceae, Asteraceae, and *Sarcobatus* occurred, which is consistent with the grassy-steppe environment described in other studies (Leopold and Denton, 1987; Mustoe and Leopold, 2014; Viney et al., 2017). It is important to point out that *Pterocarya* is also absent, but it was in high abundance during the Poison Creek and Chalk Hills depositional times. The palynomorphs observed for the Glenns Ferry Formation in this study were also reported for the Horse Quarry in Hagerman Fossil Beds National Monument by Mustoe and Leopold (2014). The vegetation in the Pliocene in the basin is comparable to the native vegetation in the Boise area today. Desert vegetation and grasses predominate, whereas larger coniferous trees grew in the uplands near water drainages.

Producing Zones and Petroleum Play Elements

The producing sand reservoirs in the Willow field (termed the 'Willow,' 'DJS,' and other unnamed sands by Bridge Resources Corp., Paramax Resources Ltd., and Alta Mesa Services LP) occur ~1,970 ft (~600 m) above the top of the first volcanic unit encountered in the subsurface and are perforated in the Payette and Poison Creek Formations. The main producing zones are between 3,770 and 4,260 ft (1,150–1,300 m MD; Fig. 11). Another hydrocarbon-bearing zone is at 5,905 ft (1,800 m MD), as identified in the petrophysical logs and well logging reports. There is one reservoir sand in the Chalk Hills Formation that provided the first hydrocarbons produced in Idaho in the State 1-17 well between the depth of 1,847 and 2,000 ft (563–610 m; termed the 'Hamilton' or 'upper sands'). This producing zone only occurs in the Willow field, and is not present in the other fields; it is 2,300–3,300 ft (~700–1,000 m) above the first volcanic unit.

The producing zones in the Harmon field are ~985–2,300 ft (~300–700 m) above the first volcanic unit, and are also in the Payette and Poison Creek Formations between ~3,400 and 3,960 ft (1,036–1,207 m) deep. The Harmon field production of thermogenic wet gas is from medium- to coarse-grained arkosic sands, some sands coarsening upward and with shaley interbeds characteristic of fan deltas, and with thicknesses up to 200 ft (61 m). The Willow and Harmon fields (Fig. 3) have proven to be the "sweet spots" where liquid condensate, natural gas, and oil occur. In the Hamilton field to the south, the source may have become over-mature with laterally discontinuous isolated channel forms, resulting in little to no hydrocarbons.

Many of the Willow and Harmon field wells have drilled through basalt sills below 3,800 ft (-1,600 ft elevation). Sills are typically 13–260 ft (4–80 m) thick, and may influence both structure and thermal maturation of the hydrocarbon occurrences (Wood, 2019). Volcanic rocks were drilled in the deeper wells (> 6,000 ft depth [> 1,828 m]) of the Willow field and shallower in updip wildcat wells to the northeast, and these are considered silicic and basaltic flows of the Weiser volcanic field.

Identification of source rocks for these hydrocarbons is an unresolved problem. Cuttings logs of Willow field wells DJS Properties1-14 (depth of 4,950–5,000 ft [1,508–1,524 m]) and DJS Properties 1-15 (depth of 3,840–3,980 ft [1,170–1,213 m) record ~50–140 ft (15–43 m) of dark gray to black shale with coal in the deeper section. The May 1-13 well logged 260 ft (80 m) dark gray shale with carbonaceous partings 5,200–5,460 ft (1,585–1,665 m). Some of these cutting samples are 3–5% organic carbon. In outcrop, the Payette Formation contains 8–20 in (20–50 cm) coal beds that are interbedded with 6–24 in (15–60 cm) organic-rich mudstone in the Indian Creek locality (Paddock Valley Reservoir quadrangle; Figs. 3 and 5). Total coal in the section is 4 ft (1.2 m), with interbeds of organic rich mudstone that total up to 6 additional ft (1.8 m) (Feeney et al., 2016). These appear to be the most promising source rocks to date. Perhaps the Payette Formation is only one contributor to the hydrocarbons and other organic-rich rocks—possibly from the Mesozoic accreted terrane rocks at depth or to the north (Mann and Vallier, 2007) may also be contributors.

Fluvial, deltaic, backswamp, and smaller restricted lacustrine depositional environments of the Payette and Poison Creek Formations provided sedimentary packages with thick reservoir sands. The bentonitic tuffaceous mudstones, which dominate the Chalk Hills Formation, most likely act as a sealing facies and overburden for the oil, condensate, and natural gas to the underlying Poison Creek and Payette Formations below. The Glenns Ferry Formation most likely acts as additional overburden to the petroleum system in the subsurface.

This hydrocarbon play contains a source that underwent an optimal maturation window in some parts of the basin. From the new 9.04, 9.01, and 7.78 Ma dates, we suspect that the burial of the source rocks began about 10 to 12 Ma. Deposition continued until ~5 to 6 Ma when another exposure event occurred. Further burial occurred as the sedimentary rocks of the Glenns Ferry Formation were deposited into the basin ~4 to 5 Ma. The combination of lithostatic pressure from the overburden of the Chalk Hills and Glenns Ferry sediments, sag, and down-dropping by a series of extensional faulting aided in the burial of the source rocks further until depths of thermal maturity were reached. In addition, basalt sill intrusions thought to be younger than 11 Ma (Wood, 2019) most likely increased the geothermal gradient in the basin as well, which aided maturation of the hydrocarbons. Broad folds and normal faults expressed at the surface suggest that these structures may form traps in the subsurface. Both 2D and 3D seismic surveys have been acquired and processed, but are not available to the authors. More detailed fault and trap structure information is likely recorded by that data.

To summarize, a Wheeler diagram was created from Weiser to Mountain Home (Fig. 12). The Payette Formation is restricted to the area near Weiser and Horseshoe Bend, Idaho, and does not extend as far as Mountain Home. It is interbedded with and overlies the CRBG and WVF. The Poison Creek Formation is also largely restricted to the western part of the basin. Figure 12 shows the facies changes within the study area through geological time and space. Although Wheeler diagrams commonly show eustatic changes, this figure shows lake level changes and local accommodation versus exposure over time.

CONCLUSIONS

Correlation to the subsurface data using palynomorph biostratigraphic markers for the first time aid in the correlation of key producing horizons in the nearby Hamilton, Willow, and Harmon oil and gas fields. New U–Pb ages support surficial and subsurface mapping and help outline major basin formation and subsidence amongst major regional volcanic activity. The reduction or disappearance of some warmer-climate deciduous trees (*Platanus, Liquidambar,* and *Pterocarya)* is an indicator of cooling, and are critically diagnostic for biostratigraphic correlation. The presence of grasses alongside sagebrush (*Artemisia* spp.) and saltbush (Chenopodiaceae) also indicates a general cooling.

The Payette Formation is the sedimentary section interbedded within and deposited above the early Miocene volcanic units north of the WSRP. Here, we newly define the Payette Formation to be strata locally overlying the uppermost Miocene volcanic unit in the regional as well as the sedimentary interbeds between the CRBG and WVF. Thickness may be as much as ~3,500 ft (~1,000 m), but thinner where the sedimentary section above the last volcanic unit has been eroded. It locally contains organic material (especially near Horseshoe Bend) and mid-Miocene climatic optimum floral assemblages. Kirkham (1931) suggested that the Payette Formation was only interbedded with volcanic rocks, but our mapping and

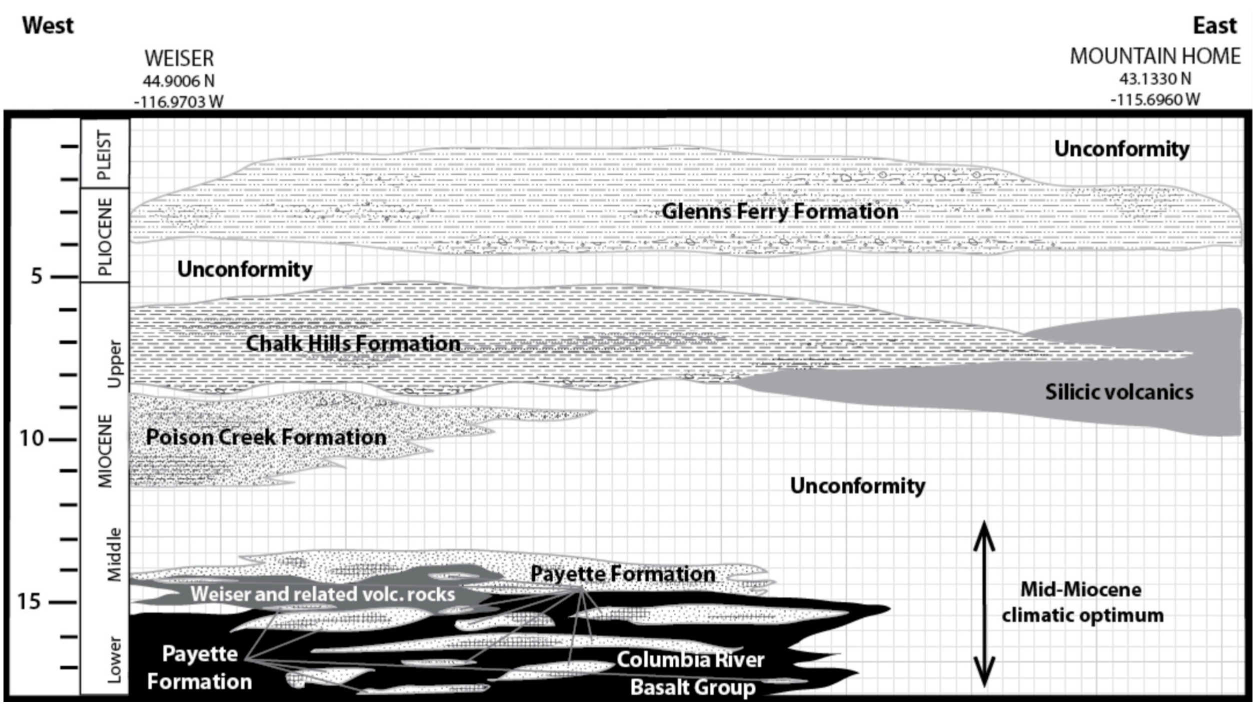


Figure 12. Wheeler diagram showing chronostratigraphic relationship and major hiatuses. Note: The Payette and Poison Creek Formations are only in the western part of the diagram. The Chalk Hills and Glenns Ferry Formations are much more laterally extensive (full extent not shown here). Vertical scale is age in millions of years.

dating indicate that it is both interbedded and overlies the CRBG and WVF.

The Poison Creek Formation overlies the Payette Formation in the area northwest of Emmett. It typically occurs as a sandy interval 800–1,800 ft (250–550 m) thick that is commonly the first producing hydrocarbon zone in the Willow and Harmon fields. This thickness contrasts with the type section in Poison Creek, south of the WSRP, which is roughly 100–400 ft (30–120 m) thick (Buwalda, 1923; Malde and Powers (1962). Based on our new U–Pb ages, we suggest that the Poison Creek Formation is between 11 and 9 Ma, but could be as old as 11.5 Ma and as young as 8.5 Ma. An unconformity between the Payette and Poison Creek Formations likely causes the uppermost- and lowermost-dated deposits to differ across the basin. Less certain is the extent, if any, of a hiatus between deposition of the Poison Creek and Chalk Hills Formations. There is also a persistent unconformity at the base of the Glenns Ferry Formation, further skewing correlations and correct thicknesses across the mapping area. The thickness of the Chalk Hills Formation is up to 4,200 ft (1,280 m) in some wells, but absent east of Emmett. The Glenns Ferry Formation between Emmett and Payette is only ~500 ft (~150 m) thick, because much has been eroded.

ACKNOWLEDGMENTS

The authors thank Mark Barton for discussions regarding the sequence stratigraphy of the oil and gas fields of southwest Idaho, and Patrick Fields and William Rember for helpful discussions about plant micro and macrofossils. We also thank reviewers Nathan Carpenter, Paul Link, and Jason McClaughry, and *Rocky Mountain Geology* Science Co-Editors Art Snoke and Ron Frost for their review of this manuscript. Finally, we thank the numerous landowners in the Emmett and Payette area for access, without which this research and subsequent report would not have been possible.

REFERENCES CITED

Allen, C.M., and Campbell, I.H., 2012, Identification and elimination of a matrix-induced systematic error in LA–ICP–MS $^{206}Pb/^{238}U$ dating of zircon: Chemical Geology, v. 332–333, p. 157–165.

Armstrong, R.L., Leeman, W.P., and Malde, H.E., 1975, K–Ar dating, Quaternary and Neogene volcanic rocks of the Snake River Plain, Idaho: American Journal of Science, v. 275, p. 225–251.

Ashwill, M.S., 1983, Seven fossil floras in the rain shadow of the Cascade Mountains, Oregon: Oregon Geology, v. 45, p. 107–111.

Axelrod, D.I., 1964, The Miocene Trapper Creek flora of southern Idaho: University of California Publications in Geological Sciences, v. 51, 148 p.

Baghai, N.L., and Jorstad, R.B., 1995, Paleontology, paleoclimatology and paleoecology of the late middle Miocene Musselshell Creek flora, Clearwater County Idaho: A preliminary study of a new fossil flora: Palaios, v. 10, p. 424–436.

Barry, T.L., Kelley, S.P., Reidel, S.P., and five others, 2013, Eruption chronology of the Columbia River Basalt Group, *in* Reidel, S.P., Camp, V.E., Ross, M.E., and four others, eds., The Columbia River flood basalt province: Boulder, Colorado, Geological Society of America Special Paper 497, p. 45–66.

Barton, M.D., 2019, Idaho Geological Survey Oil & Gas Program: GeoNote 46: Idaho Geological Survey, 10 p., https://www.idahogeology.org/product/g-46.

Benson, T.R., and Mahood, G.A., 2016, Geology of the mid-Miocene Rooster Comb caldera and Lake Owyhee volcanic field, eastern Oregon: Silicic volcanism associated with Grande Ronde flood basalt: Journal of Volcanology and Geothermal Research, v. 309, p. 96–117.

Benson, T.R., Mahood, G.A., and Grove, M., 2017, Geology and $^{40}Ar/^{39}Ar$ geochronology of the middle Miocene McDermitt volcanic field, Oregon and Nevada: Silicic volcanism associated with propagating flood basalt dikes at initiation of the Yellowstone hotspot: Geological Society of America Bulletin, v. 129, p. 1,027–1,051.

Bestland, E.A., Forbes, M.S., Krull, E.S., and two others, 2008, Stratigraphy, paleopedology, and geochemistry of the middle Miocene Mascall Formation (type area, central Oregon, USA): PaleoBios, v. 28, p. 41–61.

Bingham, J.W., and Grolier, M.J., 1966, The Yakima Basalt and Ellensburg Formation of south-central Washington: Contributions to Stratigraphy: U.S. Geological Survey Bulletin 1124-G, *iii* + p. G1–G15.

Black, C.C., 2021, Rhyolite stratigraphy along Succor Creek: Insights into the eruptive history of the Three Fingers and Mahogany Mountain volcanic field [Master's thesis]: Portland, Oregon, Portland State University, Paper 5799, *xi* + 155 p., https://doi.org/10.15760/etd.7670.

Bond, J.G, Kauffman, J.D., Rember, W.C., and Shiveler, D.J., 2011, Weiser Basin evaluation: Idaho Geological Survey Technical Report T-11-1, *v* + 125 p., 1 sheet.

Bonnichsen, B., Boroughs, S., Godchaux, M.M, and Wolff, J., 2016, From land to lake: Basalt and rhyolite volcanism in the western Snake River Plain, Idaho, *in* Lewis, R.S., and Schmidt, K.L., eds., Exploring the geology of the Inland Northwest: Geological Society of America Field Guide 41, p. 93–125.

Bowen, C.F., 1913, Coal at Horseshoe Bend and Jerusalem Valley, Boise County, Idaho: *in* Campbell, M.R., geologist in charge, Contributions to economic geology (short papers and preliminary reports), 1911: Part II, Mineral fuels: U.S. Geological Survey Bulletin 531, p. 245–262, 1 sheet.

Breedlovestrout, R., and Lewis, R.S., 2017, Connecting geologic mapping to subsurface well logs to explore Idaho's first producing hydrocarbon field in Payette County: Geological Society of America Abstracts with Programs, v. 49, no. 6.

Breedlovestrout, R., Lewis R.S., Isakson V., and two others, 2017, Mapping of Miocene-Pliocene Lake Idaho and Payette sedimentary deposits north of the western Snake River Plain: Geological Society of America Abstracts with Programs, v. 49, no. 6.

Buechler, W.K., Dunn, M.T., and Rember, W.C., 2007, Late Miocene Pickett Creek flora of Owyhee County, Idaho: Ann Arbor, University of Michigan, Contributions from the Museum of Paleontology, v. 31, p. 305–362.

Buwalda, J.P., 1923, A preliminary reconnaissance of the gas and oil possibilities of southwestern and south-central Idaho: Idaho Bureau of Mines and Geology Pamphlet 5, 10 p.

___ 1924, The age of the Payette Formation and the old erosion surface in Idaho: Science, v. 60, p. 572–573.

Cahoon, E.B., Streck, M.J., Koppers, A.A.P., and Miggins, D.P., 2020, Reshuffling the Columbia River Basalt chronology—Picture Gorge Basalt, the earliest- and longest- erupting formation: Geology, v. 48, p. 348–352, https://doi.org/10.1130/G47122.1.

Camp, V.E., and Ross, M.E., 2004, Mantle dynamics and genesis of mafic magmatism in the intermontane Pacific Northwest: Journal of Geophysical Research: Solid Earth, v. 109, B08204, 14 p., https://doi.org/10.1029/2003JB002838.

Camp, V.E., Ross, M.E., Duncan, R.A., and four others, 2013, The Steens Basalt: Earliest lavas of the Columbia River Basalt Group, *in* Reidel, S.P., Camp, V.E., Ross, M.E., and four others, eds., The Columbia River flood basalt province: Boulder, Colorado, Geological Society of America Special Paper 497, p. 87–116.

Capps, S.R., 1941, Faulting in western Idaho, and its relation to the higher placer deposits: Idaho Bureau of Mines and Geology Pamphlet 56, *iii* + 20 p.

Chaney, R.W., and Axelrod, D.I., 1959, Miocene floras of the Columbia Plateau: Carnegie Institution of Washington Publication 617, p. 1–134.

Condon, D.J., Schoene, B., McLean, N.M., and two others, 2015, Metrology and traceability of U–Pb isotope dilution geochronology (EARTHTIME Tracer Calibration Part I): Geochimica et Cosmochimica Acta [Geochemistry and Cosmochemistry Transactions], v. 164, p. 464–480.

Cope, E.D., 1883, A new Pliocene formation in the Snake River valley: American Naturalist, v. 17, p. 867–868.

Cummings, M.L., Evans, J.G., Ferns, M.L., and Lees, K.R., 2000, Stratigraphic and structural evolution of the middle Miocene synvolcanic Oregon-Idaho graben: Geological Society of America Bulletin, v. 112, p. 668–682.

Davis, O.K., and Ellis, B.S., 2010, Early occurrence of sagebrush steppe, Miocene (12 Ma) on the Snake River Plain: Review of Palaeobotany and Palynology, v. 160, p. 172–180.

Dillhoff, R.M., Dillhoff, T.A., Dunn, R.E., and two others, 2009, Cenozoic paleobotany of the John Day Basin, central Oregon, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to vineyards: Geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 135–164.

Downing, K.F., 1992, Biostratigraphy, taphonomy, and paleoecology of vertebrates from the Sucker Creek Formation (Miocene) of southeastern Oregon [Ph.D. dissert]: Tucson, University of Arizona, 24 p.

Downing, K.F., and Swisher, C.C., III, 1993, New $^{40}Ar/^{39}Ar$ dates and refined geochronology of the Sucker Creek Formation, Oregon: Journal of Vertebrate Paleontology, v. 13, p. 33A.

Eldridge, G.H., 1896, A geological reconnaissance across Idaho, *in* Walcott, C.D., Sixteenth annual report of the United States Geological Survey to the Secretary of the Interior, 1894-1895: Part II - Papers of an economic character: U.S. Geological Survey Annual Report 16, p. 211–276.

Feeney, D.M., and Schmidt, K.L., 2019, Geologic map of Crane Creek Reservoir quadrangle, Washington County, Idaho: Idaho Geological Survey Digital Web Map DWM-187, scale 1:24,000, 1 sheet.

Feeney, D.M., Isakson, V.H., Lewis, R.S., and Mertzman, S.A., 2017, Mapping middle Miocene volcanic rocks in the Weiser embayment, southwest Idaho: New U–Pb TIMS zircon age data and its implications: Geological Society of America Abstracts with Programs, v. 49, no. 6, https://gsa.confex.com/gsa/2017AM/webprogram/Paper307041.html.

Feeney, D.M., Wood, S.H., Lewis, R.S., and three others, 2018, Geologic map of the northeast Emmett quadrangle, Gem County, Idaho: Idaho Geological Survey Digital Web Map DWM-185, scale 1:24,000, 1 sheet.

Feeney, D.M., Wood, S.H., Sundell, A.J., and two others, 2023, Geologic map of the Paddock Valley Reservoir quadrangle, Payette and Washington counties, Idaho:

Idaho Geological Survey Digital Web Map, scale 1:24,000, 1 sheet (in press).

Ferns, M.L. and McClaughry, J.D., 2013, Stratigraphy and volcanic evolution of the middle Miocene to Pliocene La Grande–Owyhee eruptive axis in eastern Oregon, *in* Reidel, S.P., Camp, V.E., Ross, M.E., and four others, eds., The Columbia River flood basalt province: Geological Society of America Special Paper 497, p. 401–427.

Ferns, M.L., Streck, M.J. and McClaughry, J.D., 2017. Field-trip guide to Columbia River flood basalts, associated rhyolites, and diverse post-plume volcanism in eastern Oregon: U.S. Geological Survey Scientific Investigations Report 2017-5022-O, *xii* + 71p.

Fields, P.F., 1983, A review of the Miocene stratigraphy of southwestern Idaho, with emphasis on the Payette Formation and associated floras [Master's thesis]: University of California, Berkeley, 386 p.

___ 1996, The Succor Creek flora of the middle Miocene Sucker Creek Formation, southwestern Idaho and eastern Oregon: systematics and paleoecology [Ph.D. dissert.]: Lansing, Michigan State University, *xx* + 675 p.

Fitzgerald, J.F., 1982, Geology and basalt stratigraphy of the Weiser embayment, west-central, Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 103–128.

Forester, C.S., and Wood, S.H., 2012, Geologic map of the Holland Gulch quadrangle, Payette and Washington counties, Idaho: Idaho Geological Survey Technical Report T-12-1, scale 1:24,000, 1 sheet.

Garwood, D.L., Feeney, D.M., Phillips, W.M., and Cooley, S.W., 2014, Geologic map of the Nutmeg Flat quadrangle, Washington County, Idaho: Idaho Geological Survey Digital Web Map DWM-168, scale 1:24,000, 1 sheet.

Gilbert, J.D., Piety, L., and LaForge, R., 1983, Seismotectonic study, Black Canyon Diversion Dam and Reservoir, Boise Project, Idaho: U.S. Bureau of Reclamation Seismotectonic Report 83-7, 73 p., 8 sheets.

Graham, A., 1963, Systematic revision of the Sucker Creek and Trout Creek Miocene floras of southeastern Oregon: American Journal of Botany, v. 50, p. 921–936.

Haq, B.U., Hardenbol, J.A.N., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1,156–1,167.

Hart, W.K., and Brueseke, M.E., 1999, Analysis and dating of volcanic horizons from Hagerman Fossil Beds National Monument and a revised interpretation of eastern Glenns Ferry Formation chronostratigraphy: National Park Service Report 1443-PX9608-97-003, 37 p.

Hearst, J.M., 1999, The mammalian paleontology and depositional environments of the Birch Creek local fauna (Pliocene: Blancan), Owyhee County, Idaho, [Ph.D. dissert.]: Lawrence, University of Kansas, 431 p.

Hooper, P.R., Camp, V.E., Reidel, S.P., and Ross, M.E., 2007, The origin of the Columbia River flood basalt province: Plume versus nonplume models, *in* Foulger, G.R., and Jurdy, D.M., eds., Plates, plumes, and planetary processes: Boulder, Colorado, Geological Society of America Special Paper 430, p. 635–668.

Izett, G.A., 1981, Volcanic ash beds: Recorders of upper Cenozoic silicic pyroclastic volcanism in the western United States: Journal of Geophysical Research, v. 86, p. 10,200–10,222.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., and two others, 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Physical Review C, v. 4, p. 1,889–1,906.

Jarboe, N.A., Coe, R.S., Renne, P.R., and Glen, J.M.G., 2010, The age of the Steens reversal and the Columbia River Basalt Group: Chemical Geology, v. 274, p. 158–168.

Kasbohm, J., and Schoene, B., 2018, Rapid eruption of the Columbia River flood basalt and correlation with the mid-Miocene climate optimum: Science Advances, v. 4, no. 9, https://doi.org/10.1126/sciadv.aat8223.

Kimmel, P.G., 1979, Stratigraphy and paleoenvironments of the Miocene Chalk Hills Formation and Pliocene Glenns Ferry Formation in the western Snake River Plain, Idaho [Ph.D. dissert.]: Ann Arbor, University of Michigan, 331 p.

___ 1982, Stratigraphy, age, and tectonic setting of the Miocene-Pliocene lacustrine sediments of the western Snake River Plain, Oregon and Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 559–578.

Kirkham, V.R.D., 1930, Old erosion surfaces in southwestern Idaho: The Journal of Geology, v. 38, p. 652–663.

___ 1931, Revision of the Payette and Idaho Formations: The Journal of Geology, v. 39, p. 193–239.

Kirkham, V.R.D., and Johnson, M.M., 1929, The Latah Formation in Idaho: The Journal of Geology, v. 37, p. 483–504.

Knowlton, F.H., 1926, Flora of the Latah formation of Spokane, Washington, and Coeur d'Alene, Idaho, *in* Mendenhall, W.C., chief geologist, Shorter contributions of general geology, 1925: U.S. Geological Survey Professional Paper 140-A (Part II), p. 17–81.

Knudsen, K.L., Simpson, G.D., Sawyer, T.L., and four others, 1996, Late Quaternary faulting and seismotectonics of east-central Oregon and west-central Idaho: Geological Society of America Abstracts with Programs, v. 28, no. 5, p. 82.

Kohn, M.J., Miselis, J.L., and Fremd, T.J., 2002, Oxygen isotope evidence for progressive uplift of the Cascade Range, Oregon: Earth and Planetary Science Letters, v. 204, p. 151–165.

Lawrence, D.C., 1988, Geology and revised stratigraphic interpretation of the Miocene Sucker Creek Formation, Malheur County, Oregon [Master's thesis]: Boise, Idaho, Boise State University, 67 p.

Leopold, E.B., and Denton, M.F., 1987, Comparative age of grassland and steppe east and west of the Northern Rocky Mountains: Annals of the Missouri Botanical Garden, v. 74, p. 841–867.

Lewis, R.S., Love, R.L., Wood, S.H., and three others, 2023, Geologic map of the Sheep Ridge quadrangle, Payette County, Idaho: Idaho Geological Survey Digital Web Map, scale 1:24,000, 1 sheet (in press).

Lewis, R.S., Phillips, W.M., Feeney, D.M., and two others, 2016, Geologic map of the Montour quadrangle, Boise and Gem counties, Idaho: Idaho Geological Survey Digital Web Map DWM-177, scale 1:24,000, 1 sheet.

Lindgren, W., 1898, The mining districts of the Idaho Basin and the Boise Ridge, Idaho: U.S. Geological Survey Annual Report 18: Part III—Economic geology, p. 617–744.

Link, P.K., McDonald, H.G., Fanning, C.M., and Godfrey, A.E., 2002, Detrital zircon evidence for Pleistocene drainage reversal at Hagerman Fossil Beds National Monument, central Snake River Plain, Idaho, *in* Bonnichsen, B., White, C.M., and McCurry, M., eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Idaho Geological Survey Bulletin 30, p. 105–119.

Love, R.L., Lewis R.S., and Feeney, D.M., 2023, Geologic map of the Hog Cove Butte 7.5′ quadrangle, Gem and Payette counties, Idaho: Idaho Geological Survey Digital Web Map, scale 1:24,000, 1 sheet (in press).

Ludwig, K.R., 2003, User's manual for Isoplot 3.00: A geochronological toolkit for Microsoft Excel, Berkeley Geochronology Center: Berkeley, California, Special Publication 4, 70 p.

Macdonald, F.A., Schmitz, M.D., Strauss, J.V., and six others, 2018, Cryogenian of Yukon: Precambrian Research, v. 319, p. 114–143.

Mackin, J.H., and Cary, A.S., 1965, Origin of Cascade landscapes: Washington Division of Mines and Geology Information Circular 41, *vii* + 35 p.

Mahood, G.A., and Benson, T.R., 2017, Using $^{40}Ar/^{39}Ar$ ages of intercalated silicic tuffs to date flood basalts: Precise ages for Steens Basalt Member of the Columbia River Basalt Group: Earth and Planetary Science Letters, v. 459, p. 340–351.

Malde, H.E., 1972, Stratigraphy of the Glenns Ferry Formation from Hammett to Hagerman, Idaho: U.S. Geological Survey Bulletin 1331-D, *iii* + 19 p.

___ 1991, Quaternary geology and structural history of the Snake River Plain, Idaho and Oregon, *in* Morrison, R.B., ed., Quaternary nonglacial geology: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The geology of North America, v. K-2, p. 251–281, https://doi.org/10.1130/DNAG-GNA-K2.251.

Malde, H.E., and Powers, H.A. 1962, Upper Cenozoic stratigraphy of western Snake River Plain, Idaho: Geological Society of America Bulletin, v. 73, p. 1,197–1,220.

Mann, G.A., and Vallier, T.L., 2007, Mesozoic telescoping of island-arc terranes and geologic evolution of the Cuddy Mountains region, western Idaho, *in* Kuntz, M.A., and Snee, L.W., eds., Geological studies of the Salmon River suture zone and adjoining areas, west-central Idaho and eastern Oregon: U.S. Geological Survey Professional Paper 1738, p. 163–180.

Mattinson, J.M., 2005, Zircon U–Pb chemical abrasion ("CA-TIMS") method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: Chemical Geology, v. 220, p. 47–66.

McClaughry, J.D., Ferns, M.L., and Gordon, C.L., 2021, Geology of the north half of the lower Crooked River Basin, Crook, Deschutes, Jefferson, and Wheeler counties, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 108, *ix* + 286 p. text, 1 sheet, scale 1:63,360.

McKay, D.I.A., Tyrrell, T., Wilson, P.A., and Foster, G.L., 2014, Estimating the impact of the cryptic degassing of large igneous provinces: A mid-Miocene case-study: Earth and Planetary Science Letters, v. 403, p. 254–262.

McLean, N.M., Condon, D.J., Schoene, B., and Bowring, S.A., 2015, Evaluating uncertainties in the calibration of isotopic reference materials and multi-element isotopic tracers (EARTHTIME Tracer Calibration Part II): Geochimica et Cosmochimica Acta [Geochemistry and Cosmochemistry Transactions], v. 164, p. 481–501.

Mitchell, S.G., and Montgomery, D.R., 2006, Polygenetic topography of the Cascade Range, Washington State, USA: American Journal of Science, v. 306, p. 736–768, https://doi:10.2475/09.2006.03.

Mustoe, G.E., and Leopold, E.B., 2014, Paleobotanical evidence for the post-Miocene uplift of the Cascade

Range: Canadian Journal of Earth Sciences, v. 51, p. 809–824.

Nasdala, L., Lengauer, C.L., Hanchar, J.M., and five others, 2002, Annealing radiation damage and the recovery of cathodoluminescence: Chemical Geology, v. 191, p. 121–140.

Nash, B.P., and Perkins, M.E., 2012, Neogene fallout tuffs from the Yellowstone hotspot in the Columbia Plateau region, Oregon, Washington and Idaho, USA: PloS ONE, v. 7, no. 10: e44205, https://doi.org/10.1371/journal.pone.0044205.

Neville, C., Opdyke, N.D., Lindsay, E.H., and Johnson, N.M., 1979, Magnetic stratigraphy of Pliocene deposits of the Glenns Ferry Formation, Idaho, and its implications for North American mammalian biostratigraphy: American Journal of Science, v. 279, p. 503–526.

Othberg, K.L., 1994, Geology and geomorphology of the Boise Valley and adjoining areas, western Snake River Plain, Idaho: Idaho Geological Survey Bulletin 29, *vi* + 54 p.

Pardee, J.T., Bryan, K., and Knowlton, F.H., 1926, Geology of the Latah formation in relation to the lavas of Columbia Plateau near Spokane, Washington, *in* Mendenhall, W.C., chief geologist, Shorter contributions of general geology, 1925: U.S. Geological Survey Professional Paper 140-A (Part I), p. 1–16.

Perkins, M.E., Brown, F.H., Nash, W.P., and three others, 1998, Sequence, age, and source of silicic fallout tuffs in middle to late Miocene basins of the northern Basin and Range province: Geological Society of America Bulletin, v. 110, p. 344–360.

Pierce, K.L., and Morgan, L.A., 1992, The track of the Yellowstone hot spot: Volcanism, faulting and uplift, *in* Link, P.K., Kuntz, M.A., and Platt, L.B., eds., Regional geology of eastern and western Wyoming: Geological Society of America Memoir 179, p. 1–53.

Reidel, S.P., Camp, V.E., Tolan, T.L., and Martin, B.S., 2013, The Columbia River flood basalt province: Stratigraphy, areal extent, volume, and physical volcanology, *in* Reidel, S.P., Camp, V.E., Ross, M.E., and four others, eds., The Columbia River flood basalt province: Boulder, Colorado, Geological Society of America Special Paper 497, p. 1–43.

Reidel, S.P., Martin, B.S., and Petcovic, H.L., 2003, The Columbia River flood basalts and the Yakima fold belt, *in* Swanson, T.W., ed., Western Cordillera and adjacent areas: Boulder, Colorado, Geological Society of America Field Guide 4, p. 87–105.

Reidel, S.P., Tolan, T.L., Hooper, P.R., and four others, 1989, The Grande Ronde Basalt, Columbia River Basalt Group: Stratigraphic descriptions and correlations in Washington, Oregon, and Idaho, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Boulder, Colorado, Geological Society of America Special Paper 239, p. 21–53.

Reiners, P.W., Ehlers, T.A., Garver, J.I., and four others, 2002, Late Miocene exhumation and uplift of Washington Cascade Range: Geology, v. 30, p. 676–770, https://doi.org/10.1130/0091-7613(2002)030<0767:LMEAUO>2.0.CO;2.

Repenning, C.A., Weasma, T.R., and Scott, G.R., 1995, The early Pleistocene (latest Blancan–earliest Irvingtonian) Froman Ferry fauna and history of the Glenns Ferry Formation, southwestern Idaho: U.S. Geological Survey Bulletin 2105, *iv* + 86 p.

Rivera, T.A., White, C.M., Schmitz, M.D., and Jicha, B.R., 2021, Petrogenesis of Pleistocene basalts from the western Snake River Plain, Idaho: Journal of Petrology, v. 62, egaa108, https://doi.org/10.1093/petrology/egaa108.

Savage, C.N., 1961, Geology and mineral resources of Gem and Payette counties: Idaho Bureau of Mines and Geology County Report C-4, *vii* + 50 p. text, 1 sheet, scale 1:125,000.

Schmitz, M.D., and Schoene, B., 2007, Derivation of isotope ratios, errors, and error correlations for U-Pb geochronology using ^{205}Pb-^{235}U-(^{233}U)-spiked isotope dilution thermal ionization mass spectrometric data: Geochemistry, Geophysics, Geosystems, v. 8, Q08006, 20 p., https://doi.org/10.1029/2006GC001492.

Shah, S.M.I., 1966, Stratigraphy and paleobotany of the Weiser area [Master's thesis]: Moscow, University of Idaho, 191 p.

___ 1968, Stratigraphic paleontology of the Weiser area, Idaho [Ph.D. dissert.]: Moscow, University of Idaho, 166 p.

Shervais, J.W., Shroff, G., Vetter, S.K., and three others, 2002, Origin and evolution of the western Snake River Plain: Implications from stratigraphy, faulting, and the geochemistry of basalts near Mountain Home, Idaho, *in* Bonnichsen, B., White, C.M., and McCurry, M., eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Idaho Geological Survey Bulletin 30, p. 343–361.

Smiley, C.J., 1963, The Ellensburg flora of Washington: University of California Publications in Geological Sciences, v. 35, p. 159–276.

___ 1989, The Miocene Clarkia fossil area of northern Idaho: Idaho Geological Survey Bulletin 28, p. 35–48.

Smiley, C.J., and Rember, W.C., 1985, Composition of the Miocene Clarkia flora, *in* Smiley, C.J., ed., Late Cenozoic history of the Pacific Northwest: Interdisciplinary studies on the Clarkia fossil beds of northern Idaho: San Francisco, California, American

Association for the Advancement of Science, Pacific Division, Annual Meeting, p. 95–112.

Smiley, C.J., Gray, J., and Huggins, L.M., 1975, Preservation of Miocene fossils in unoxidized lake deposits, Clarkia, Idaho; with a section on fossil Insecta by W.F. Barr and J.M. Gillespie: Journal of Paleontology, v. 49, p. 833–844.

Smith, G.A., 1988a, Neogene synvolcanic and syntectonic sedimentation in central Washington: Geological Society of America Bulletin, v. 100, p. 1,479–1,492.

___ 1988b, Sedimentology of proximal to distal volcaniclastics dispersed across an active foldbelt: Ellensburg Formation (late Miocene), central Washington: Sedimentology, v. 35, p. 953–977.

Smith, H.V., 1938, Some new and interesting late Tertiary plants from Sucker Creek, Idaho-Oregon boundary. Torrey Botanical Club Bulletin, v. 65, p. 557–564.

Smith, R.B., and Braile, L.W., 1994, The Yellowstone hotspot: Journal of Volcanology and Geothermal Research, v. 61, p. 121–187.

Smith, G., and Cossel, J., Jr., 2002, Fishes from the late Miocene Poison Creek and Chalk Hills Formations, Owyhee County, Idaho, *in* Akersten, W.A., Thompson, M.E., Meldrum, D.J., and two others, eds., Papers on the vertebrate paleontology of Idaho honoring John A. White, v. 2: Pocatello, Idaho Museum of Natural History Occasional Paper 37, p. 23–35.

Smith, G.A., Shafiqullah, M., Campbell, N.P., and Deacon, M.W., 1989, Geochronology of the Ellensburg Formation—Constraints on Neogene volcanism and stratigraphic relationships in central Washington: Isochron/West, v. 53, p. 28–32.

Smith, G.R., Morgan, N., and Gustafson, E., 2000, Fishes of the Mio-Pliocene Ringold Formation, Washington: Pliocene capture of the Snake River by the Columbia River: Ann Arbor, University of Michigan Papers on Paleontology, v. 32, *vi* + 47 p.

Smith, G.R., Swirydczuk, K., Kimmel, P.G., and Wilkinson, B.H., 1982, Fish biostratigraphy of late Miocene to Pleistocene sediments of the western Snake River Plain, Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 519–541.

Sosdian, S.M., Babila, T.L., Greenop, R., and two others, 2020, Ocean carbon storage across the middle Miocene: A new interpretation for the Monterey Event: Nature Communications, v. 11, p. 1–11.

Streck, M.J., Ferns, M.L., and McIntosh, W., 2015, Large, persistent rhyolitic magma reservoirs above Columbia River Basalt storage sites: The Dinner Creek Tuff eruptive center, eastern Oregon: Geosphere, v. 11, p. 226–235.

Swanson, D.A., Wright, T.L., Hooper, P.R., and Bentley, R.D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, *iv* + 59 p.

Swirydczuk, K., Larson, G.P., and Smith, G.R., 1982, Volcanic ash beds as stratigraphic markers in the Glenns Ferry and Chalk Hills Formations from Adrian, Oregon, to Bruneau, Idaho, *in* Bonnichsen, B., and Breckenridge, R.M., eds., Cenozoic geology of Idaho: Idaho Bureau of Mines and Geology Bulletin 26, p. 543–558.

Swirydczuk, K., Wilkinson, B.H., and Smith, G.R., 1979, The Pliocene Glenns Ferry oolite; lake-margin carbonate deposition in the southwestern Snake River Plain: Journal of Sedimentary Research, v. 49, p. 995–1,004.

___ 1980, The Pliocene Glenns Ferry oolite; II, Sedimentology of oolitic lacustrine terrace deposits: Journal of Sedimentary Research, v. 50, p. 1,237–1,247.

Taggart, R.E., and Cross, A.T., 1990, Plant successions and interruptions in Miocene volcanic deposits, Pacific Northwest: Boulder, Colorado, Geological Society of America Special Paper 244, p. 57–68, https://doi.org/10.1130/SPE244-p57.

Taggart, R.E., Cross, A.T., Dilcher, D.L., and Taylor, T.N., 1980, Vegetation change in the Miocene Sucker Creek flora of Oregon and Idaho: A case study in paleosuccession. biostratigraphy of fossil plants, *in* Dilcher, D.L., and Taylor, T.N., eds., Biostratigraphy of fossil plants: Successional and paleoecological analyses: Stroudsburg, Pennsylvania, Dowden, Hutchinson & Ross Inc., p. 185–221.

Viney, M., Mustoe, G.E., Dillhoff, T.A., and Link, P.K., 2017, The Bruneau Woodpile: A Miocene phosphatized fossil wood locality in southwestern Idaho, USA: Geosciences, v. 7, no. 3, 25 p.

Warner, M.M., 1975, Special aspects of Cenozoic history of southern Idaho and their geothermal implications, *in* Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975: Washington, D.C., U.S. Government Printing Office (Lawrence Berkeley Laboratory, University of California) p. 653–664.

___ 1981, Cenozoic marker beds of southern Idaho, *in* Aram, R.B., ed., Guidebook to southwest Montana: Montana Geological Society Field Conference and Symposium, p. 121–124.

Washburne, C.W., 1911, Gas and oil prospects near Vale, Oregon, and Payette, Idaho, *in* Campbell, M.R., geologist in charge, Contributions to economic geology (short papers and preliminary reports), 1909: Part II, Mineral fuels: U.S. Geological Survey Bulletin 431, p. 26–55.

Wendt, I., and Carl, C., 1991, The statistical distribution of the mean squared weighted deviation: Chemical Geology: Isotope Geoscience section, v. 86, p. 275–285.

Wheeler, H.E., and Cook, E.F., 1954, Structural and stratigraphic significance of the Snake River capture, Idaho-Oregon: The Journal of Geology, v. 62, p. 525–536.

Wolfe, J.A., 1995, Paleoclimatic estimates from Tertiary leaf assemblages: Annual Review of Earth and Planetary Sciences, v. 23, p. 119–142.

Wood, S.H., 1994. Seismic expression and geological significance of a lacustrine delta in Neogene deposits of the western Snake River plain, Idaho: AAPG Bulletin, v. 78, p. 102–121.

Wood, S.H., 2019, Multiple basalt sill intrusions into the Miocene Payette/Drip Springs and lower Chalk Hills Formation sediments, 1.4–2.4 km deep beneath Ontario, Oregon: Identification and significance for western Snake River Plain stratigraphy: Geological Society of America Abstracts with Programs, v. 51, no. 4, doi:10.1130/abs/2019CD-328995.

___ 2004, Geology across and under the western Snake River Plain, Idaho: Owyhee Mountains to the Boise foothills (Chapter 7), *in* Haller, K.M., and Wood, S.H., eds., Geological field trips in southern Idaho, eastern Oregon, and northern Nevada: U.S. Geological Survey Open-File Report 2004-1222, p. 85–107.

Wood, S.H., and Clemens, D.M., 2002, Geologic and tectonic history of the western Snake River Plain, Idaho and Oregon, *in* Bonnichsen, B., White, C.M., and McCurry, M., eds., Tectonic and magmatic evolution of the Snake River Plain volcanic province: Idaho Geological Survey Bulletin 30, p. 69–103.

You, Y., Huber, M., Müller, R.D., and two others, 2009, Simulation of the middle Miocene climate optimum: Geophysical Research Letters, v. 36, no. 4, https://doi.org/10.1029/2008GL036571.

Zachos, J.C., Pagani, M.O., Sloan, L.C., and two others, 2001, Trends, rhythms, and aberrations in global climate 65 Ma to present: Science, v. 292, p. 686–693.

Zachos, J.C., Dickens, G.R., and Zeebe, R.E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics: Nature, v. 451, p. 279–283.

Science Editors: B. Ronald Frost and Arthur W. Snoke